

## 1. Introduction

As part of the rehabilitation for those with congenital upper-limb loss or limb amputation a prosthesis can be prescribed (Barsby et al 1995). Whether amputees' lose one arm (unilateral amputation) or both arms (bilateral amputation) they have a need to appear 'normal'. Additionally, bilateral amputees, and those with high level amputations have a particular need for prosthetic devices that will restore some of the functions of the lost limb.

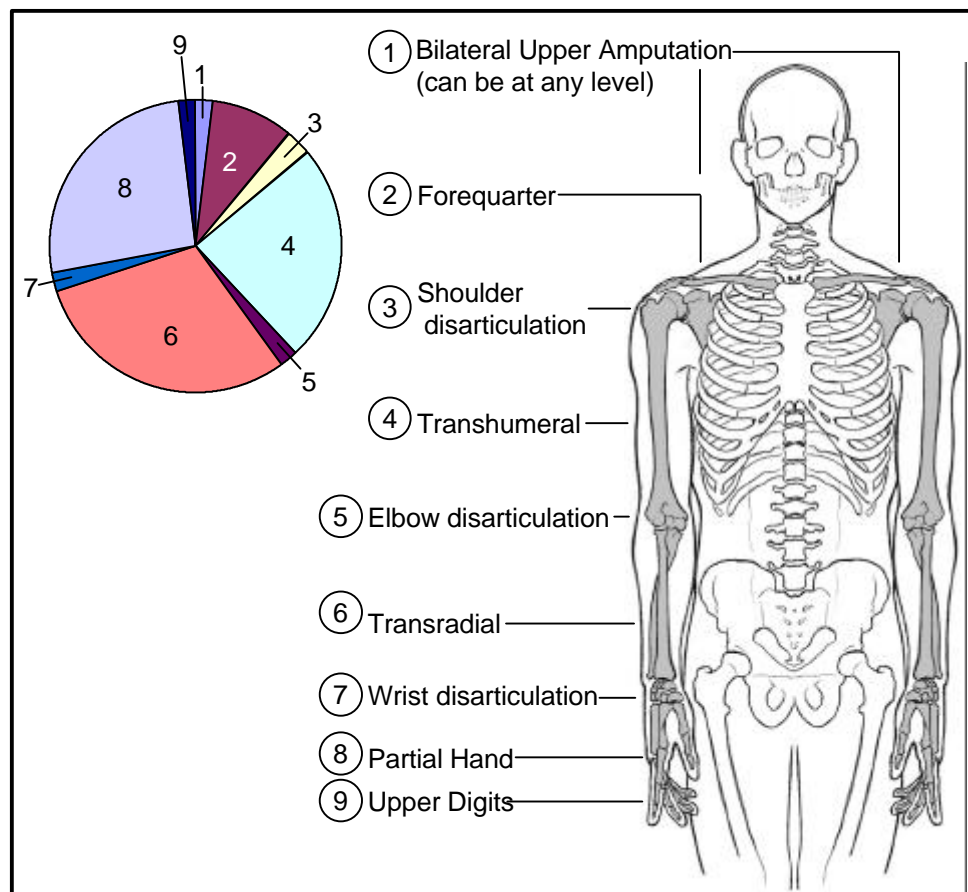
Current prostheses available to the amputee have developed in small steps from a limited number of moderately successful initial archetypes. The continued development of prostheses from these archetypes has resulted in the separation of prostheses into those that offer the outward appearance of the lost limb and those that offer some functionality.

From reference to previous research (Kejlaa 1993, Burger and Marincek 1993) as well as both formal and informal discussions with amputees over a long period it is apparent that current prostheses do not meet the needs or aspirations that amputees have for a future prosthesis.

This chapter reviews the situation of the amputee; the reasons for limb loss, how this effects the amputee and what prostheses are commercially available to help the amputee. A history of the different prosthetic devices then given, followed by a description of the technological limitations that have been cited as reasons for previous research in this field being discontinued.

Additionally, complementary research into the fields of robotics is reported that demonstrates some of the design problems faced in prosthetics are not unique to this field.

Diagrams have been included to explain the terminology associated with these fields which will continue to be used throughout the main body of work.



**Fig 1.1 The Levels of Recorded Limb Loss in 1998 (NASDAB 1999)**

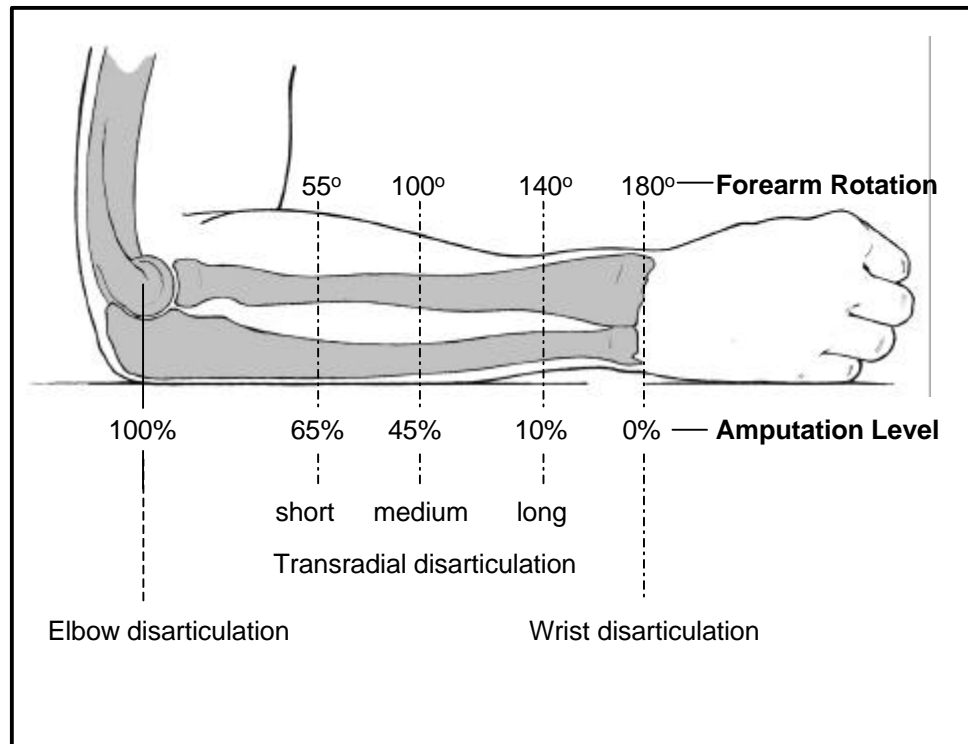
There are records on approximately nine thousand upper-limb amputees held by Mobility and Specialised Rehabilitation Centres in the UK (Barsby *et al* 1995). The pie chart above shows how the total number of the 253 recorded referrals made to prosthetic service centres in the UK for 1998, splits into levels of amputation. The total number upper-limb amputees represents approximately 5% of the total number of amputations in this period. The majority of referrals are male 71.5%, with traumatic amputations accounting for 56% of the cases of limb loss (NASDAB 1999).

Loss of the upper-limb can be traumatic (through accident, injury or disease) or congenital (missing or imperfectly formed from birth).

Congenital absences are classified according to the missing bony segments which may be longitudinal or transverse (Barsby *et al* 1995).

An example of a longitudinal absence might be the absence of a finger of the hand or an absent humerus within an otherwise complete limb.

Transverse absences are more akin to traumatic amputations (Barsby *et al* 1995) and refer to the deficiency of all bony segments beyond a certain transverse level.

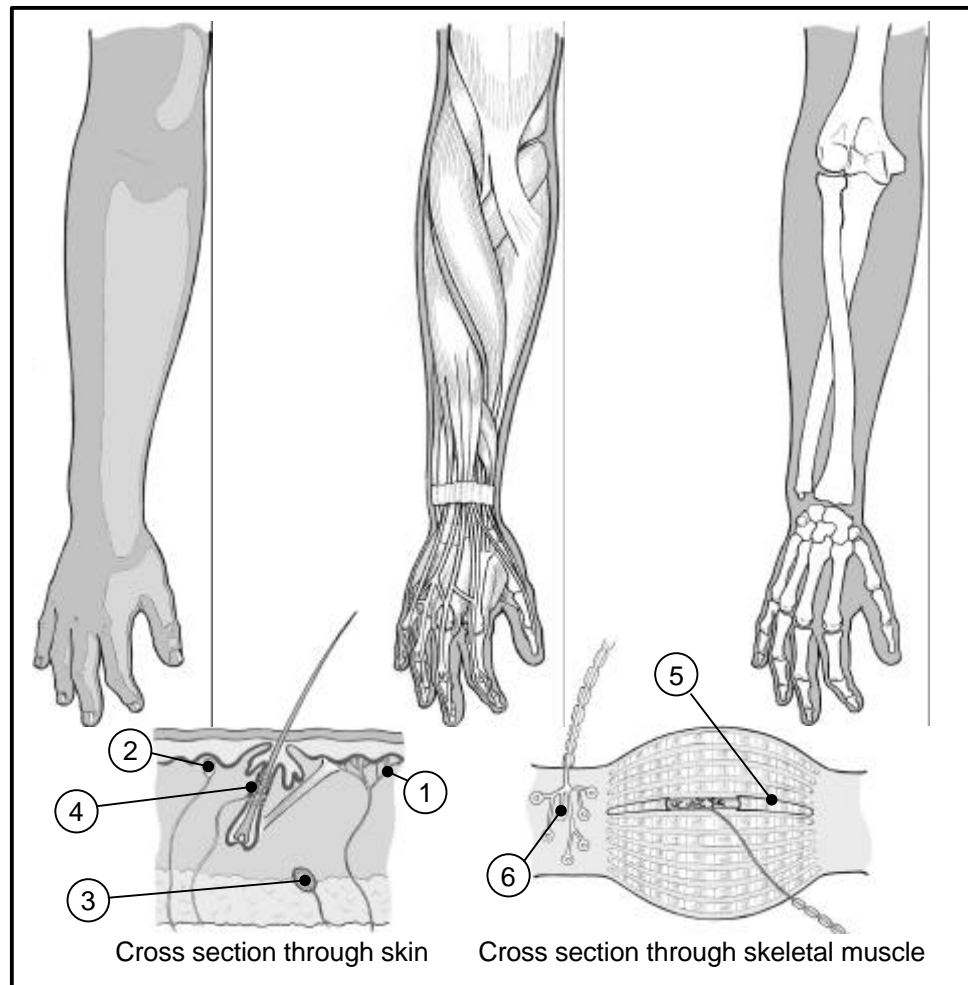


**Fig 1.2 Levels of Forearm Amputation** (Bennett Wilson 1989)

The general surgical procedure for traumatic amputation is to leave as much of the length of the limb as possible, taking account of the size and type of prosthesis that may be subsequently fitted (Kostuik 1980).

The chief cause of the most proximal amputation, the forequarter amputation is for conditions such as osteosarcoma of the shoulder girdle. This amputation includes removal of the whole arm including the scapula and clavicle (Kostuik 1980). Road traffic accidents, industrial accidents and burns are the main cause of the remaining levels of amputation (Barsby *et al* 1995).

Activities of daily living (ADL) become increasingly difficult for the amputee as the level of amputation progresses upwards (Robertson 1978). Figure 1.2 shows how the range of forearm rotation diminishes as the level of amputation progresses up the limb, demonstrating that the functionality of the remaining limb is affected by the position of amputation (Bennett Wilson 1989).



**Fig 1.3 The Human Upper-Limb**

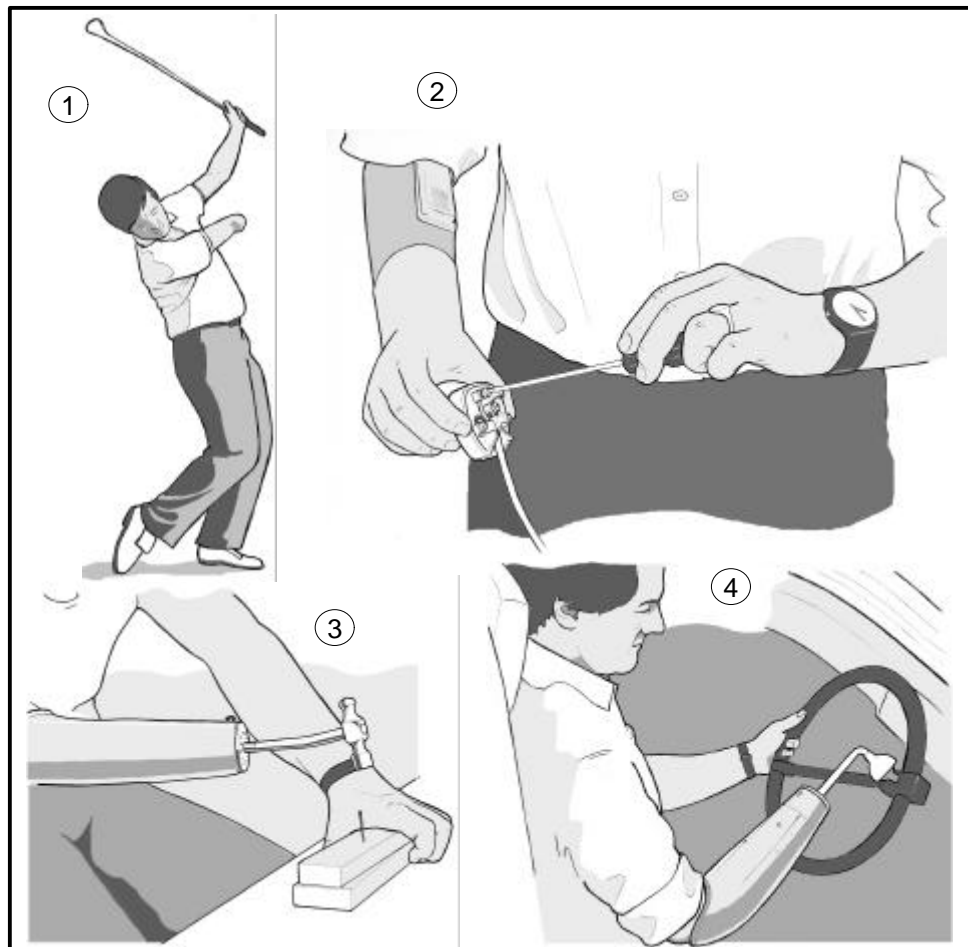
To understand the disabling nature of losing a limb it is important know a little of the anatomy and physiology of the human upper-limb.

The human upper-limb contains 36 bones, linked to muscular tissue that results in an highly dextrous manipulator with approximately 42 degrees of freedom (Reichardt 1978).

The skin of the upper-limb has many types or sensory receptors (sensors). Free dendritic (branched) nerve endings (1) sense temperature, providing the sensations of hot and cold. Other dendritic nerve endings are encapsulated within various bulbous structures, such as Meissner (2) and Pacinian corpuscles (3). These provide the sensations of touch and pressure. Whilst free nerve endings wrapped around the root of hair follicles, provide further touch sensations (4) (Fox 1993).

The musculature of the limb, along with providing actuation for the limb, contains receptors that enable the human to know where the limb is in space without looking, and how much pressure the limb is exerting; known as proprioception (Harbres et al 1974 (a)). Proprioceptive receptors that convey muscular length information are named spindle cells (5), those that detect tension applied by the muscle are Golgi tendon organs (6).

Therefore, when an upper-limb has been lost not only are the appearance and manipulative functions of the limb lost but also a major means of gathering sensory information (Kyberd 1990).

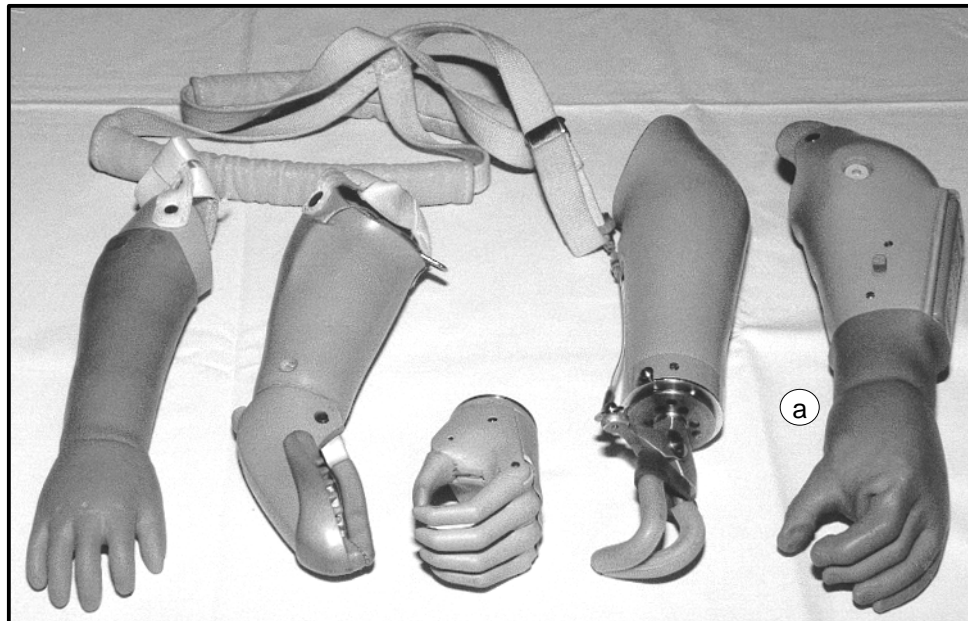


**Fig 1.4 The Need for a Prosthesis**

Amputees losing a single arm (unilateral) can adapt and function in the short-term without the aid of prosthesis (Scott and Parker 1988). Indeed figure 1.4(1) outlined from a photograph, demonstrates that, with adaptation of their golf swing, talented unilateral amputees can be competitive golfers. However, general dependence on the remaining upper-limb can lead to serious overuse syndromes (Jones and Davidson 1999).

The use of a prosthesis can assist the amputee in performing activities associated with daily living (ADL) (Kejlää 1993). Unfortunately, whether the unilateral amputee loses their dominant or subdominant hands, the current functionality of prostheses dictate that the remaining limb will become the dominant limb and the prosthesis will only serve as an assistive device (Scott and Parker 1988). Figure 1.4.(2), again outlined from a photograph, demonstrates how unilateral amputees utilise their prostheses in an assistive manner to hold objects whilst the dextrous manipulations are performed with the remaining natural limb.

To perform certain tasks amputees often find that purpose designed tool-like terminal devices are more functional than hand shaped devices. (Banerjee 1982). Figures 1.4 (3) shows how a hammer is more easily used when connected directly to the socket of a prosthesis than via a prosthetic hand. Figure 1.4 (4) displays that how a ball and socket joint is commonly used as a device for steering a car. Bayonet fittings at the end of the socket provide a quick change facility for such tool-like terminal-devices.



**Fig 1.5 Prostheses Currently available to Amputees**

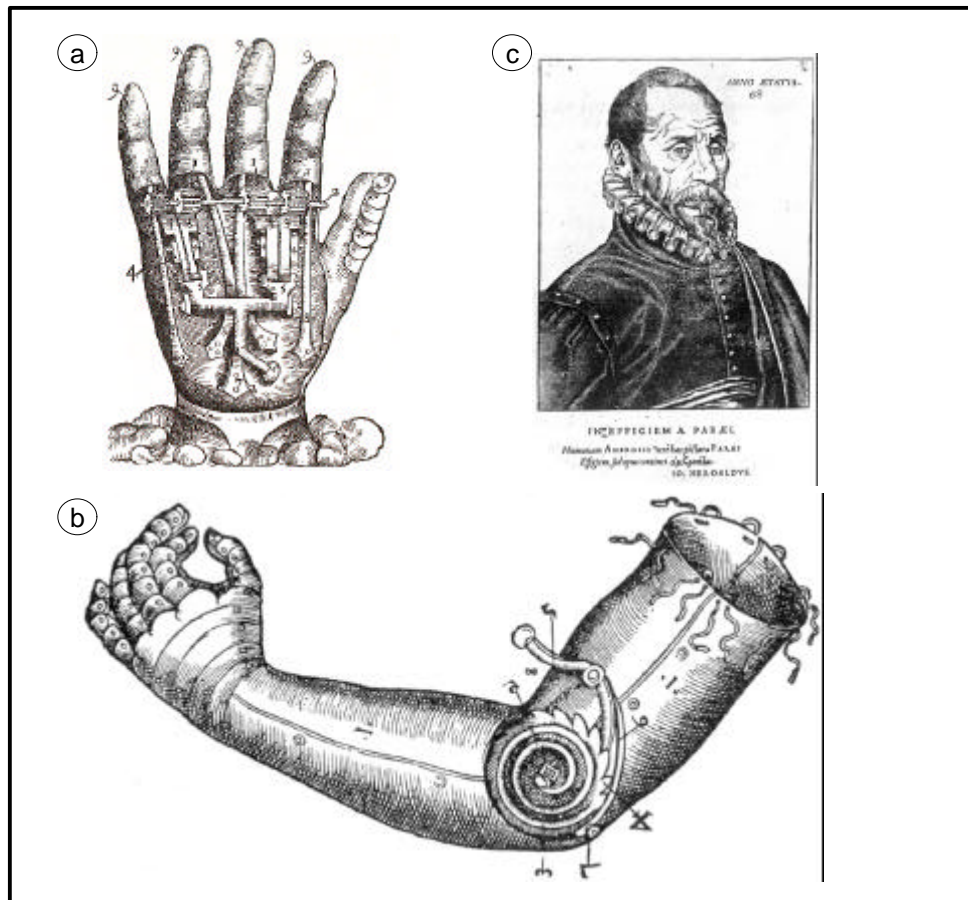
The separation of prostheses into those that are tool-like and those that only give the appearance of a human limb has resulted in prostheses being categorised cosmetic or functional.

Amputees require both the appearance of the lost limb (cosmesis) and its functionality; however, due to the limitations of current devices amputees are required to choose which attribute they prioritise. Although some amputees own an additional device that complements some attributes of their main prosthetic choice.

Current commercial designs that aim to combine both attributes of cosmesis and function provide the amputee with a compromise solution. Commonly, the dexterity of the human hand is reduced to a single degree of freedom, a prehensile (gripping) action. This action is activated by mechanisms unlike those of the human limb resulting in an unsightly bulky hand form (a).

It has been stated that functional limitations of current prosthesis designs can lead the amputee to reject the prosthesis (Scott and Parker 1988). Additionally, this is compounded by false reporting in the popular media raising amputees expectations of the performance of prostheses to an unrealistic level (Curran and Hambrey 1991).

The following pages outline the history of each type of upper-limb prosthesis up to the current state of the art.

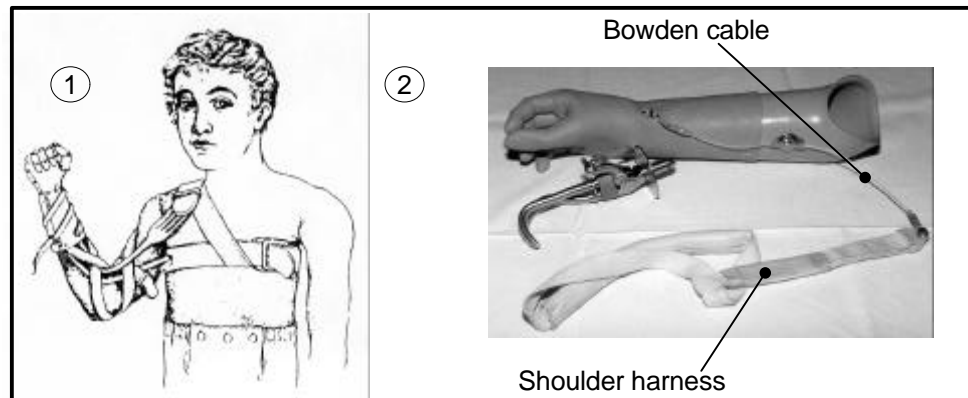


**Fig 1.6 'Le Petit Lorraine' Passive Prosthesis**

Passive prostheses have the static appearance of a human arm and hand; consequently they are referred to as cosmetic devices. They are the oldest type of upper-limb prosthesis; the first recorded being an iron hand worn by Marcus Sergius, a Roman General who lost his right hand in the Punic War (218-201 B.C.) (Banerjee 1982).

Few records remain of prostheses until the 15th century. During the 15th and 16th centuries knights who had lost limbs in battle were fitted with armour to disguise their limb loss, as limb loss was considered a sign of weakness (Kostuik 1980). Consequently, during this period prostheses were made by armourers and the needs of the civilian population were considered secondary. Figures 2.6 (a & b) show 'Le Petit Lorraine' a passive prosthesis designed by the famous military surgeon Ambrose Pare (1510-90) (c) (Reichardt 1978). Le Petit Lorraine comprises spring and ratchet systems so that the fingers and elbow could be flexed by the amputee's contralateral arm and released by levers (Reichardt 1978). It was not until detailed designs were produced by Pare, which were subsequently manufactured from moulded leather and paper by locksmiths or clockmakers, that prostheses were proposed that had the appearance of the naked human hand (Kostuik 1980).

Currently the most effective passive prostheses are individually made using silicone moulding techniques to appear very close to the appearance of the static human limb. These detail of these techniques are described later in this chapter.



**Fig 1.7 Body-Powered Prostheses**

Although many of the 15th century passive prostheses included articulations so that the prosthetic fingers could be flexed into place using the amputee's contralateral hand, it was not until 19th century that movements of the amputees body were intimately linked to those of the prosthesis.

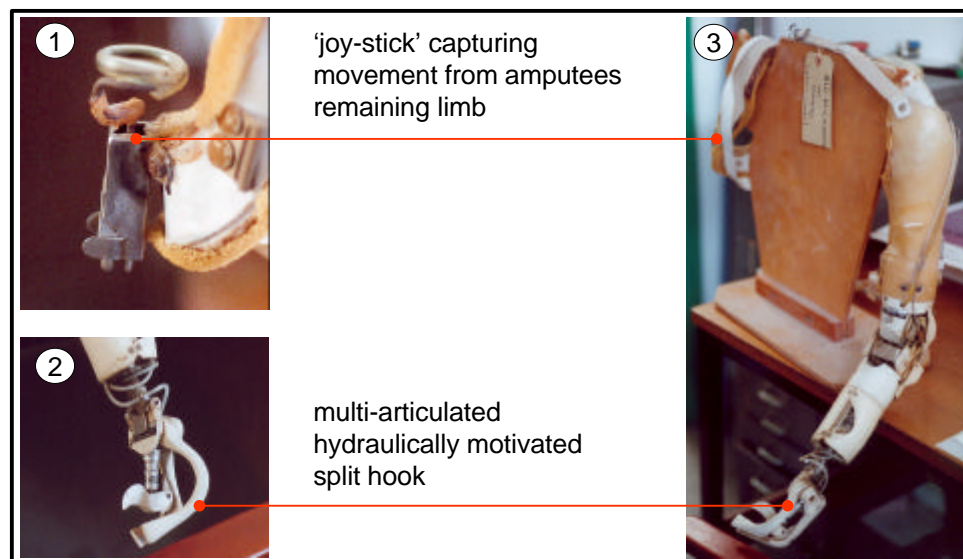
In 1812, Peter Baliff, a Berlin Dentist used leather thongs to connect the movement of an amputees shoulder and trunk to the movements of the fingers of a prosthesis shown in (1). In this way Baliff attempted to provide the amputee a means of using body-power to control and actuate the prosthesis. Baliff's design remained largely unchanged until 1944 (Banerjee 1982).

In 1944 Northrop Aviation introduced the Bowden cable which replaced connections to the amputees body made from leather thongs or linen cords (Banerjee 1982). The Bowden cable system is still in current use. For example, for the below elbow amputee; the amputees body-power is usually harnessed from bicipital abduction (rounding of the back) which produces cable excursion at one end of the Bowden cable that is transmitted to open the terminal device. Initially, body-powered prostheses used this force and movement to close the terminal device (hand or other prosthetic end effector) against the restoring force of a spring. These are referred to as "voluntary closing" devices. However, "voluntary opening" devices are more common, as voluntary closing devices are more complex and expensive (Banerjee 1982). However voluntary opening devices may also be favoured by amputees due to problems encountered by the amputee maintaining scapula abduction for grip whilst also manipulating the object (Vitali et al 1978).

The advantages of body powered devices are that they offer the amputee a mechanical link between the terminal device and their body, so that the amputee can know, without looking, where the terminal device is and (for the voluntary closing device) how much force is being applied. Additionally, body-power gained from bicipital abduction can yield large fast acting forces at the terminal device (Dalsey et al 1989). Weight has been indicated as a factor for both the comfort and function of the a prosthesis (Burger and Marincek 1994) Therefore, utilising body power requires no external power source resulting in a relatively lightweight prosthesis.

The disadvantages of the body powered prosthesis include the necessity for the amputee to wear an extensive harness to operate the device shown in figure 1.7 (2). Additionally, operation of the prosthesis requires unnatural movements that can make some tasks difficult (Kyberd 1990), as well as appearing unusual to the observer, therefore having a negative cosmetic effect.



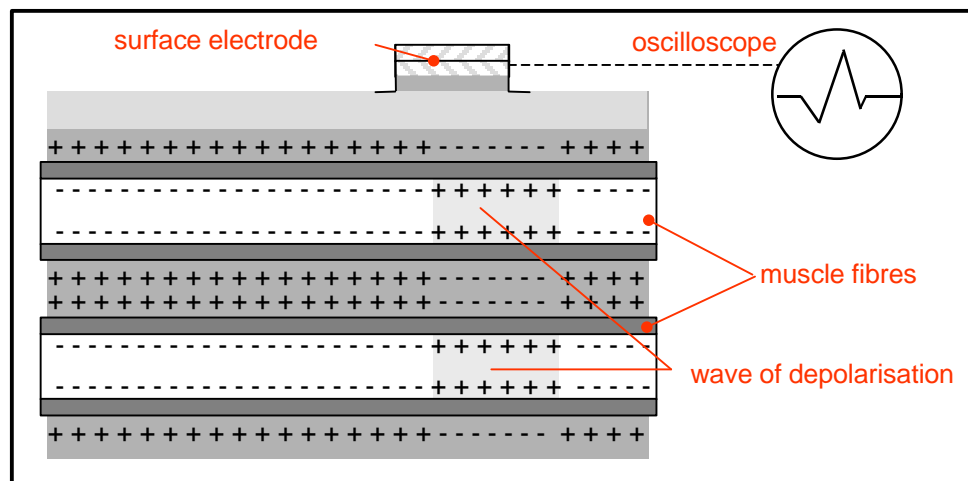


**Fig 1.8 The Hendon Hydropneumatic Prosthesis**

In the late 1940's in both Germany and the UK externally powered prostheses were being developed from aeronautical technology. These used compressed carbon dioxide as a power source (Sheridan and Mann 1978). These prostheses were developed for the needs of high level amputees who were not able to operate conventional body-powered prostheses with sufficient force (Marquardt 1965). In practice these prostheses comprised lightweight compressed carbon dioxide (CO<sub>2</sub>) canisters connected to pneumatic actuators via specially developed valve gear which was often operated by movements of the amputees trunk (Marquardt 1965).

Both this work and development on powered splints for patients suffering poliomyelitis, resulted in many novel actuator and valve designs, such as the 'Pneumatic Muscle Actuator' by McKibben (Kinnier 1965) and the joy stick valve by Hendon shown in figure 1.8 (1). The Hendon prosthesis shown uses small powerful hydraulic cylinders to actuate many degrees of freedom controlled from the joy-stick. However, hydraulic oil was considered unsuitable for prosthetic use so water was used in the cylinders. This meant that the prosthesis required regular maintenance, which ultimately led to its disuse (Kyberd 2000).

The thalidomide tragedy (1958-62) presented another great need for a successful externally powered prosthesis. The effects of the drug meant that many people were born with symmetrical abnormally short arms but highly articulate hands (Kyberd 1990), again unsuited for operating body-powered prostheses. Consequently, more research was funded into pneumatically powered arms but this was discontinued because of problems of control (Banerjee 1982). However, during this period many of the fundamental control problems were tackled by Simpson in Edinburgh - detailed later in this chapter. Therefore, discontinuation of the development may be more accurately attributed to problems associated with the unsuitability of pneumatic power to prostheses (Kyberd 1990). Such problems included the inconvenience of recharging of the CO<sub>2</sub> canisters requiring a return to a central station. The replacement of gas canisters requiring two normal hands, and in addition, in operation the pneumatic actuators produced unwanted exhaust noises (Kyberd 1990).



**Fig 1.9 Diagram of Origins of Electromyographic (EMG) Signal**

The earliest reference to an electrically powered prosthesis comes from experiments in Germany in 1918 in which the fingers of a prosthesis were flexed using electromagnets (Banerjee 1982). Further research efforts towards electrically powered prostheses commenced in the US in 1946, supported by IBM and the Veterans Association. However, after reporting impressive initial results the devices were reviewed as too complex for amputees to control (Banerjee 1982).

At the International Exhibition in Hannover in 1948 Reinhold Reiner introduced the first prosthesis to be controlled using electromyographic signals from the amputee. The control for this device was the size of a shoe box due to the technology available at the time, which is perhaps one reason why this work was overlooked until eleven years later. In 1961 Koblinsky reported the use of newly introduced transistor components to produce a similarly controlled arm with a much smaller control package that could be worn on a belt (Kostuik 1980).

Koblinsky's design aroused considerable international interest as at the time many children born with birth defects and could not use conventional body powered prostheses, and this offered a new, non-mechanical, means of control. Additionally, the Korean and Vietnam wars resulted in many US veterans demanding more technologically advanced prostheses. This led to many research programs being formed which exploited advances in micro-electronics and control system components of the early 1960's (Dalsey et al 1989).

The current generation of electrically powered prostheses utilise Reiner's electromyographic control method and are referred to as 'myoelectric' prostheses. Figure 1.9. shows the origin of the electromyographic signal and how this is detected using a surface electrode.

Each time a muscle is contracted an EMG signal is produced. The EMG signal originates from the depolarisation and repolarisation of the individual muscle cell membranes during muscular activity, this process produces measurable potential differences in the surrounding tissues which can be monitored using surface electrodes (Kostuik 1980).

The force of muscular contraction is determined by both the number of muscle fibres recruited, and by the rate at which they are activated, which is reflected in the amplitude of the EMG signal (Scott 1990).



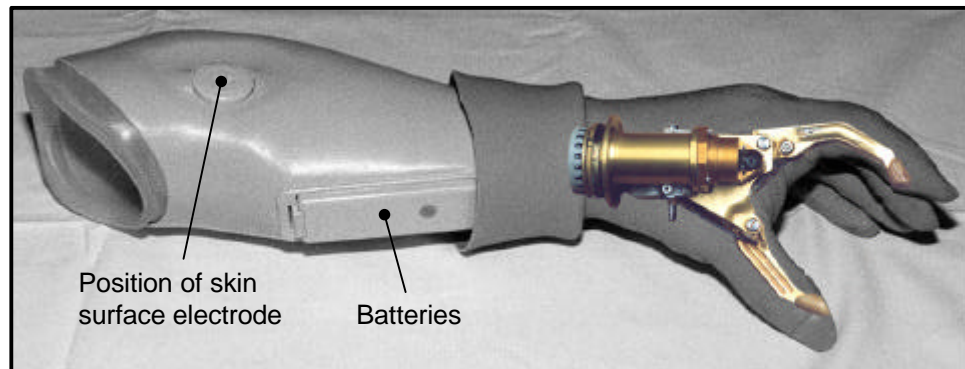
**Fig 1.10 An Otto Bock 'Myotrainer'**

Initially, it was thought that using control signals from appropriate vestigial muscle sites would form a natural link between desired action, and action completed under external power by the prosthesis (Banerjee 1982).

For a below elbow amputee the EMG may be obtained from electrodes placed over the extrinsic finger flexor and extensor muscles to switch on and off a motor to close and open the prosthetic terminal device. Early systems employed this 'two-site, two-state' control system in which the signals detected from two electrodes acted as switches with two states, off and on. However, the contraction of individual muscles is not 'natural' as muscles contract in synergies to produce joint movement (Harbers et al 1974 (1)). Therefore, amputees have to learn to control their prostheses in this way (Scott and Parker 1988). Currently, amputees are taught to produce these contractions using devices called 'myotrainers'. Early myotraining systems merely used the deflections of the needle of a sensitive volt meter to indicate levels of muscular activity (Kostuik 1980). However, figure 1.10 shows a modern Otto Bock myotrainer system suitable for both children and adults. This comprises a microcomputer screen that can be used to display a pictorial display of the actions of the proposed prosthesis as well as a depiction of the raw signal. Additionally, for children, the desired levels of muscular activity can be used to start and stop a train set, providing both a fun and emotionally more neutral means of training (Kyberd 1990).

The failure of the concept of the myoelectric prosthesis to provide a control method suitable for more proximal amputations such as those above elbow is because it is unusual to find more than one reliable EMG electrode site to control the prosthesis (Sauter 1991). This has led to systems that require a sequence of muscle contractions to produce codes to operate the prosthesis.

Such 'coded' systems include both single-site three-state controls and single-site two-state controls. The three-state system utilises a small muscular contraction to close the terminal device, and a large contraction to open it and no contraction to stop movement (Parker and Scott 1988).



**Fig 1.11 A Modern Myoelectric Prosthesis**

Single-site five-state controls have been developed to control the function of both the terminal device and a prosthetic wrist, however, this system has been found to require an excessive level of concentration from the user (otherwise known as cognitive load) that cannot justify the benefits of its multifunctionality (Scott 1990).

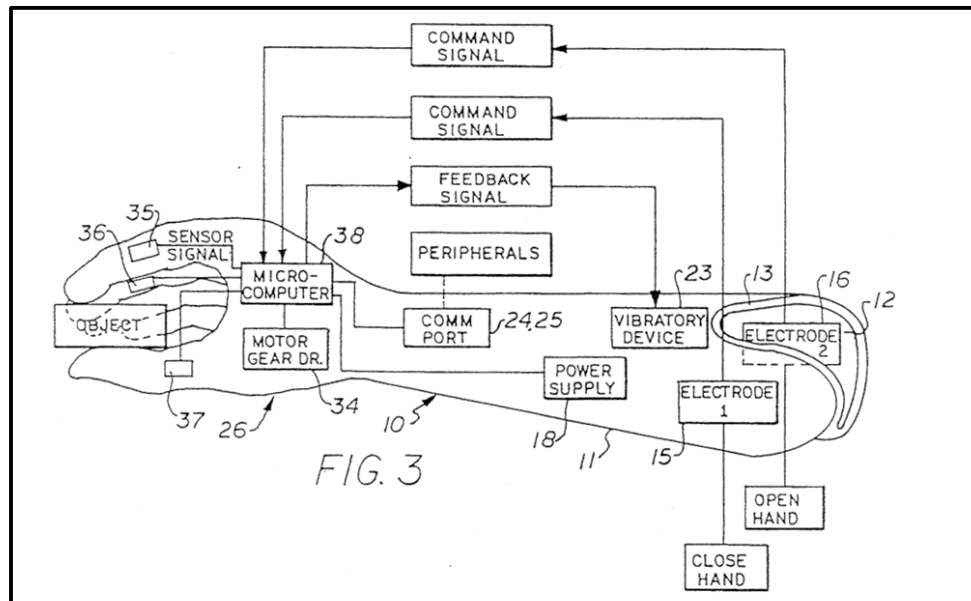
More recent clinical developments to extend the amputee's voluntary control of the prosthesis have included proportional EMG controls that estimate the level of muscle cell activity and reflect this in the rate at which the terminal device of the prosthesis is driven (Scott 1990). However, these have been criticised again as 'unnatural' as the level of muscular activity is not directly linked to the rate of contraction of the muscle (Kyberd 1994).

Using the relatively simple EMG switching control strategies described above to control more than two degrees of freedom becomes problematic for the amputee (Harbres et al 1974 (1)). However, to accomplish many of the activities of daily life, control of multiple degrees of freedom would be beneficial (Harbres et al 1974 (1), Kuribayashi 1994, Gibbons et al 1987).

Researchers addressing the need for multifunctionality have investigated both how to gain more EMG data from the amputee and how to extract more information from the EMG signal. The former studies used multiple electrodes placed on the amputee to detect patterns of synergistic muscular activity and then used these patterns to control a multiple degree of freedom prosthesis (Harbres et al 1974 (1)). Later studies looked to differences within the EMG signal from the 'cross-talk' produced when a single electrode pair was placed over two different muscles (Graupe et al 1982, Hudgins et al 1993). These systems proved relatively successful in producing volitional multifunctionality.

The principle advantages of current myoelectric prostheses are both that the remainder of the user's body is relatively unconstrained as an elaborate harness is no longer required to control the prosthesis; and that myoelectric prostheses generally possess a better cosmetic appearance than the body powered device (Datta and Ibbotson 1998). However, myoelectric prostheses are both heavier and more complex than body powered prostheses, which can result in both discomfort to the amputee and require more frequent maintenance (Datta and Ibbotson 1998).

The research discussed above on using myoelectric control principles does not address the primary problem of myoelectric control that there is an absence of sensory feed back from the prosthesis to the amputee (Banerjee 1982).

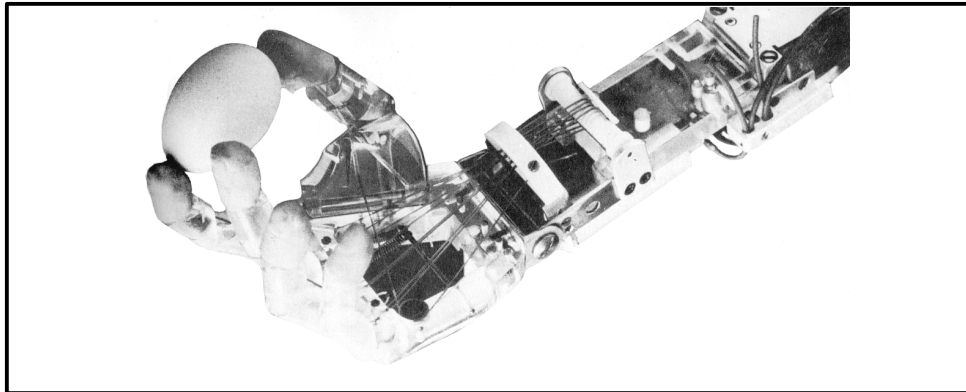


**Fig 1.12 Vibrotactile Feedback Patent Drawing** (Haslam et al 1995)

The dextrous ability of the human to control their natural upper limb effectively arises not only from multiple degrees of freedom but also from the return of afferent sensations to the nervous system and brain arising from proprioceptors in the hand and within the joints (Harbres et al 1974 (2), Banejee 1982). This sensory feedback is critical to the user in effectively controlling a prosthesis (Tura 1998). EMG signals can only provide efferent control signals to the prosthesis; that is, the control of the prosthesis is 'open-loop' (Gibbons et al 1987). Using a conventional myoelectric prosthesis the amputee has no direct means, other than visual, of knowing how much grip force is being applied or what the position of the terminal device is (Phillips 1988). Additionally, most myoelectric prostheses have a rigid socket that covers some of the amputees limb, depriving the amputee of further cutaneous (skin level) sensations (Scott and Parker 1988).

Electrotactile and vibrotactile systems have been developed to provide the user with feed-back from the prosthesis such as the one shown in figure 1.12 (Phillips 1988). Electrotactile systems return a tiny electric signal back to the skin of the remaining arm (Phillips 1988). In a similar way vibrotactile devices return a small vibration back to the amputees limb. In the example in the figure this is modulated in amplitude with reference to the force exerted by the prosthetic terminal device (Haslam et al 1995).

Both electrotactile and vibrotactile systems have been criticised as placing an unacceptable cognitive load on the amputee. That is, they require too much conscious thought on the part of the user in interpreting what the sensations mean in terms of position and force exerted by the terminal device (Harbres et al 1974 (2)). Consequently, although these devices have been patented as novel, they have not been widely implemented into commercial prostheses (Datta and Brain 1992).

**Function - Adaptable Grip Vs. Manipulation****Fig 1.13 The Collins Hand**

Adoption of the electromyographic control method into clinical practice meant that terminal devices were designed around the limitations on the number of control inputs to the prosthesis (Crossley and Umholz 1977). Using these conventional control methods amputees' can usually only reliably control a single degree of freedom at the terminal device (Aghili and Haghpahani 1995).

However, certain activities of daily living (ADL) require the simultaneous control of multiple degrees of freedom (Harbres et al 1974 (2), Barker et al 1996). Therefore, some prostheses have been designed that employ mechanisms that couple many articulations together (Crossley and Umholz 1977). These have been labelled adaptable hands, due to their adapting grip (Bergman et al 1992).

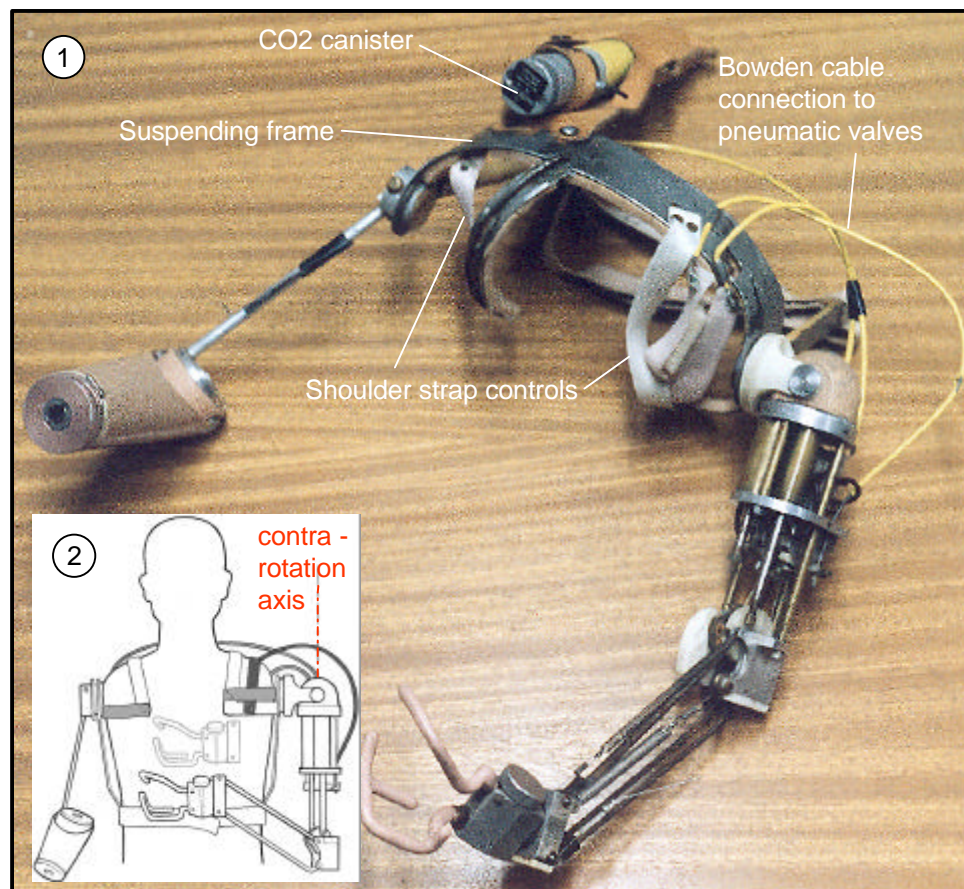
Early hand-like prostheses linked the movements of multiple fingers together. This was done using spring and balance mechanisms, similar to those that apply even tension to either side brake shoes of a car's hand brake (Kyberd 1990). This enabled the fingers of the prosthetic hand to conform around objects. (Becker, 1968)

In the early designs, cords were used to couple the flexion of all the finger segments in synchrony (Banerjee 1982). The early designs consisted of a fixed thumb, however, a later design by Collins (figure 1.13) has an similarly motivated thumb that flexes towards the palm (Reichardt 1978).

Flexing all the finger segments has also been produced through solid interconnecting struts. The Belgrade Hand (Rosheim 1994), Southampton Hand (Kyberd 1990) and various hands developed in the early 70's in Japan use this mechanism to couple flexion of all the finger segments (Kato and Sadamoto 1982). This has been done as a single linear electric motor could then be used to drive the fingers both both in flexion and extension (Kyberd 1990). However, clinical trials which compared a commercially available adaptable hand (Protesindustri AB) against a conventional myoelectric hand (Otto Bock model 8E38=7) found that amputees were able to perform key ADL's significantly better with the conventional device. Subsequently, the amputees were given both types of prostheses for a year's trial, after which all the amputees still preferred the non-adaptable hand (Bergman et al 1992).

Although grasping is a key component of dexterity, manipulation is crucial, which is defined as movement of an object within the grasp requiring independent control of the the movement of the fingers (Pons et al 1999).

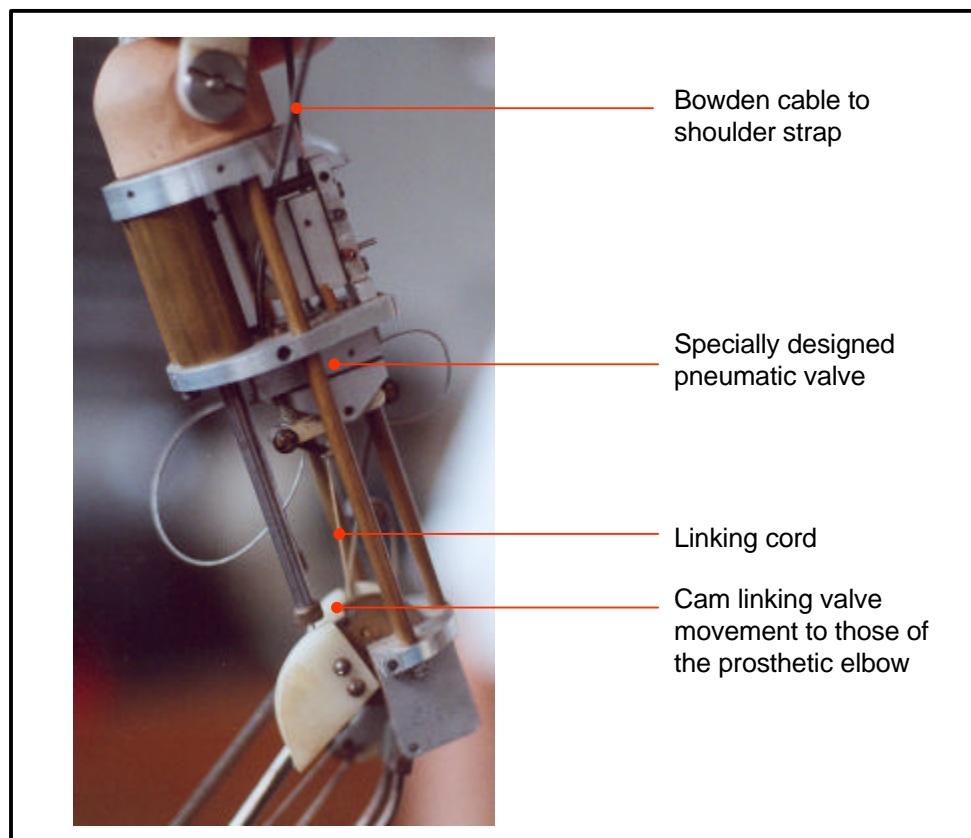




**Fig 1.14 A Simpson Pneumatic EPP Prosthesis**

The Bowden cable operated body-powered prosthesis provides a mechanical link to the amputee's body that conveys information about the position and force exerted by the terminal device (Frey and Carlson 1994). That is, one or more of the amputee's intact joints is locked to the position of a joint in the prosthesis. In this way the control method utilises the proprioceptors of the intact joints, which reduces the cognitive load (mental burden) on the amputee (Harbres 1974(2), Doubler and Childress 1984). Using this control method is said to provide the amputee with Extended Physiological Proprioception (EPP) (Harbres 1974(2)).

Figure 1.14 (1) shows an EPP prosthesis developed at Princess Margaret Rose Orthopaedic Hospital by D. C. Simpson, who has been alluded to earlier. The pneumatically powered prosthesis shown was developed for the needs of a child missing both upper-limbs due to birth defects caused by the drug Thalidomide. The principle function of the prosthesis was to assist the child in feeding activities (Gow 2000). The child operates the device through shoulder straps, (figure 1.14 (2)). Relative rotation of the child's trunk within the suspending frame, pushes on the straps (shown in grey in (2)), which opens a light pneumatic valve which causes a powered contra rotation of the prosthesis about the vertical axis shown. Elevation of the child's shoulder blades pushes on the black shoulder strap, this causes another light pneumatic valve to open to power flexion of the prosthetic elbow. Detail (2) shows how the prosthetic forearm provides a link between terminal device and elbow so that as the elbow is flexed the terminal device remains level to aid eating and drinking activities.



**Fig 1.15 Detail of Simpson's EPP Pneumatic Valve Arrangement**

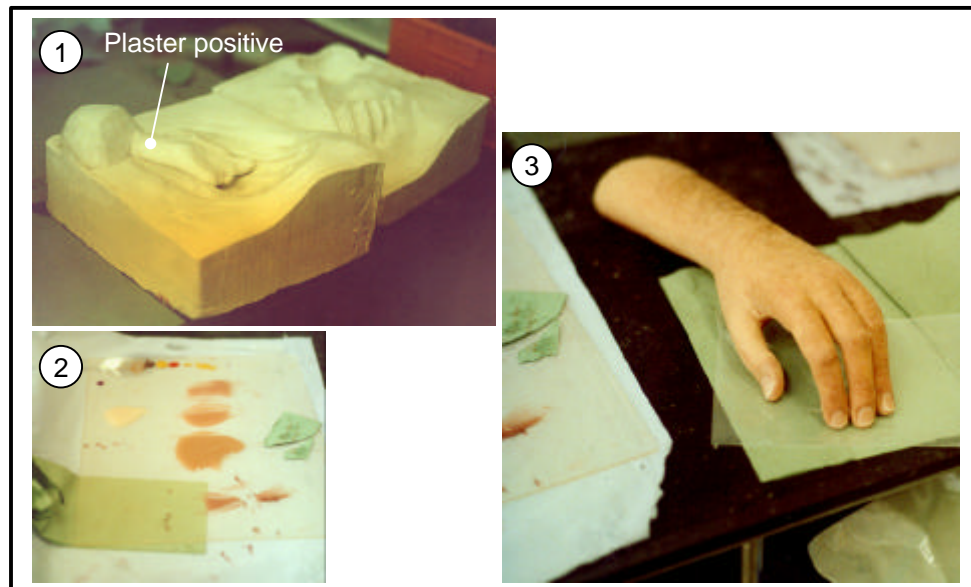
Figure 1.15 shows detail of the specially designed valve arrangement used in the previous prosthesis to control the flexion of the prosthetic elbow.

The pneumatic valve only requires a small displacement for operation, which is supplied from the Bowden cable link. However, the position of the whole valve is linked to that of the prosthetic elbow through the cord shown. Therefore, as the operators shoulder blade is raised so is the valve in a proportional manner. In this way the position of the amputees shoulder reflects that of the prosthetic elbow, even though the movement of the shoulder is significantly smaller and of less power.

Pneumatic power has a higher discharge rate when compared to electrical batteries (Datta and Brain 1992). Therefore, using pneumatic technology, Simpson was able to build a powerful, fast acting and lightweight prosthesis. However, pneumatic prostheses have many drawbacks, as mentioned earlier. These drawbacks, in conjunction with laws limiting the transportation of pneumatic canisters in the U.S., have been cited as reasons why this type of prosthesis is not now in use (Kyberd 1990).

EPP systems have been developed using electrically powered components (Doubler and Childress 1984, Baer and Seliktar 1987). However, it has been shown in such a system the input signal could 'beat' the motors ability to match this with output positioning of the prosthesis (Gibbons et al 1987). Simpson found that the exact correspondence of input to powered output is an essential feature of a system possessing EPP (Harbres et al 1974 (2)).



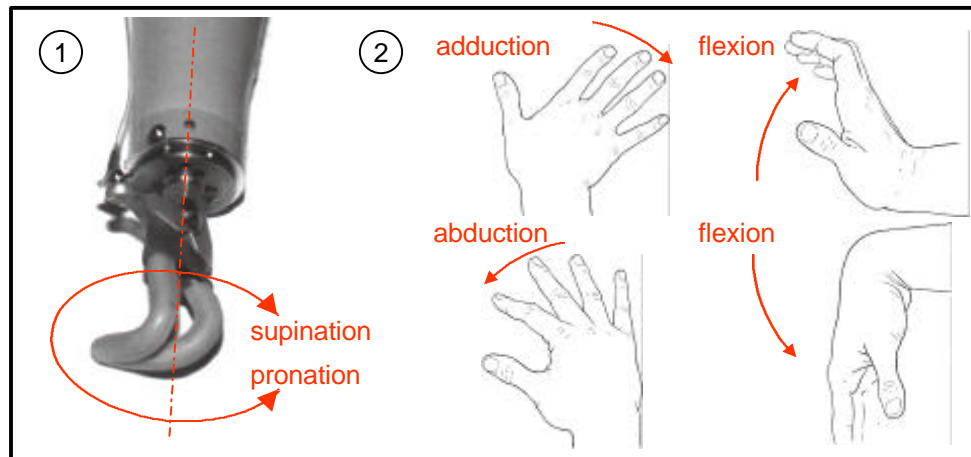


**Fig 1.16 Maxillo Facial Techniques Used to Make a Cosmetic Glove**

Alongside the functional considerations of the prosthesis, amputees have a requirement to appear 'normal' (Burger and Marincek 1994, Herder et al 1998); and for the unilateral amputee a need for bilateral symmetry (Barsby 1995). Cosmesis is the aesthetic component of a prosthesis that aims to achieve the appearance of the normal limb. Rejection of many of the functional prostheses has been directly attributed to the lack of cosmesis (Sauter 1991). It has been found that amputees only accepted externally powered prostheses when cosmetic versions became available (Sauter 1991). The lack of an acceptable prosthetic appearance can be disadvantageous for the amputee in forming normal relations with others; such problems have been documented as especially acute in the case of child amputees where parental relationships are involved (Scott 1990, Datta and Ibbotson 1998).

Using labour intensive maxillo-facial layered silicone techniques, limbs can be created by skilled practitioners that are statically indistinguishable from real limbs (Leow et al 1997). Figures 1.16 (1-3) show this technique in practice. Firstly, a mould is made of the amputee's remaining limb, a plaster 'positive' of the amputees limb is then taken from this mould. The positive is then built up with wax and sculpted to appear the form of the amputees contralateral hand. Another mould is then made of the positive and wax part combined, then the wax is melted out to leaving a mould as shown in figure 1.16 (1). Whilst the mould is split silicone is pigmented and applied to areas such as the knuckles figure 1.16 (2). Subsequently, a large quantity of base pigmented silicone is mixed and poured into the mould. Once the silicone part has been taken out further appointments are made with the amputee to apply further pigment details (Watson 2000). Figure 1.16 (3) shows how visually convincing such prostheses can be.

However, such statically convincing replicas can lead to problems for the amputee in deciding when to inform a new acquaintance that they have a missing limb. Additionally, it is documented that movement is an essential part of cosmesis (Jacobsen et al 1982, Vitali et al 1978), and the static prosthesis can promote feelings of unease in the observer due to its absence (Reichardt 1978).

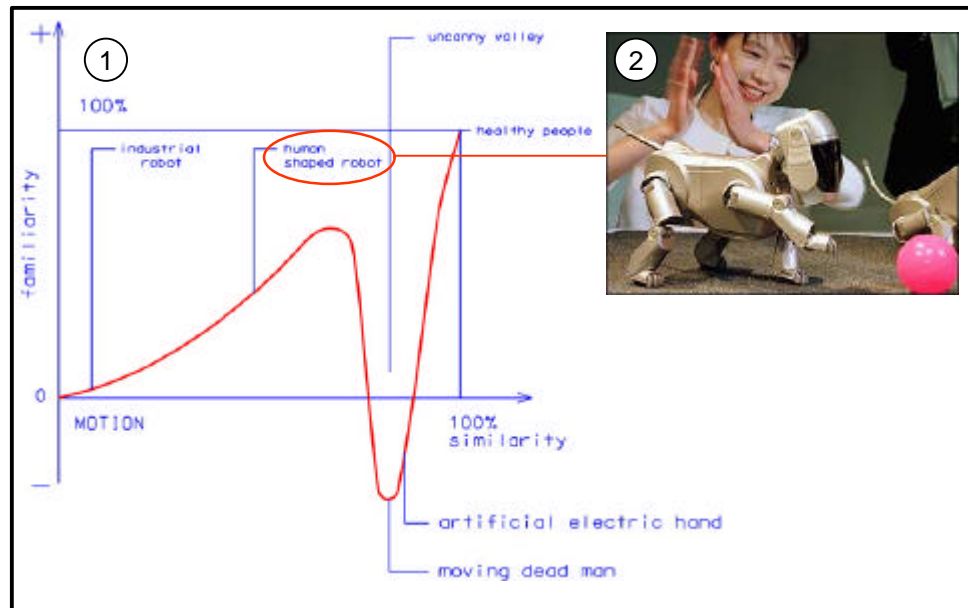


**Fig 1.17 Human and Prosthetic Wrist Movements**

There is a strong connection between, 'static cosmesis' and what has become known in the prosthetics field as 'dynamic cosmesis' (Gow 2000). Not only do the limited articulations of existing prostheses prove to be functionally limiting (Harbers et al 1974 (1)), from discussions at amputee support groups, amputees find the accessory movements they are forced to make to use their prostheses ugly. Commercially available prosthetic 'wrists' such as the example shown in figure 1.17 (1) do not provide the range of movement of the human wrist (2) (Datta and Brain 1992). This is evident when observing a transradial amputee performing tasks with a prosthesis. Positioning of the terminal device is achieved by altering the angles of the intact joints of the elbow and shoulder. Due to the distance of these joints from the terminal device, what might have been achieved through small angular adjustments at the wrist, become amplified at the elbow and shoulder. Additionally, the presence of these accessory movements have been recorded in grasping activities. It has been found that a unilateral transradial amputee grasping a cylinder with the intact hand primarily used movement of the digits, however, grasping with the prosthesis was found to include accessory movements of forearm rotation (Venkataraman and Iberall 1990).

Movement, or animation of a prosthesis, is an essential part of both cosmesis and function (Jacobsen et al 1982). Simple robotic joints result in 'singularities' which mean extra rotations often have to be performed to place the robotic terminal device where it is required (Rosheim 1994). This contrasts to human movements which are characterised by articulated joints often with multiple degrees of freedom permitting complex co-ordinated movements (Knudson and Morrison 1997).

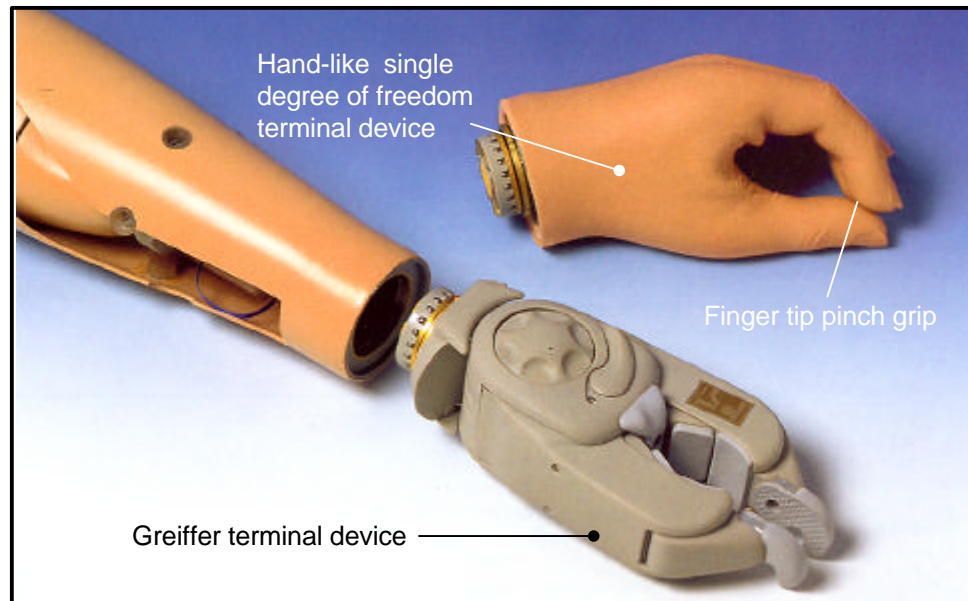
Human beings are very sensitive in observing the 'quality' of human movement (Bruderlin 1996). Human movements can be characterised by both the speed at which they are performed as well as the gross positions of the segments of the body (Knudson and Morrison 1997). For example, Japanese robotics research developed a robotic face that can perform a set of facial gestures including a smile. It was found that when the robotic smile is performed at one speed the gesture appears comforting to the observer, however, experiments with the smile at half this speed induce feelings of unease in the observer, and comments that the face is leering (Reichardt 1978). Currently, powered prostheses move much slower than the normal limb (Buckley et al 1996).



**Fig 1.18 Professor Mori's Graph and 'AIBO' The Sony Robotic Dog**

Outside the field of prosthetics the connection between static and dynamic cosmesis is also documented. The connection became evident to early motion picture animators. Animators found in the process of animating 'Snow White and the Seven Dwarfs' that the movement of the dwarfs could be conventionally animated through artistic 'inbetweening'; as these characters were clearly caricatures. However, in animating the more anthropomorphically proportioned characters such as Snow White it was found that viewers' had much higher expectations for the character to move in a convincing human-like manner. Consequently, a solution was found by filming actors acting the scenes that were subsequently traced to produce the graceful movements of Snow White in the finished film (Disney 1933). This tradition persists, both in the film industry and in computer games. Currently, movements for anthropomorphically proportioned 'virtual figures' have their movements 'motion captured' from live actors using cameras trained on 'markers' attached to the actors body (Watt 2000).

The connection of static and dynamic cosmesis has been formalised by Professor Mori. Figure 1.18 (1) shows Professor Mori's qualitative graph depicting a non-linear relationship between an observers familiarity or acceptance of an object against the human-like movement and static appearance possessed by the observed object (Reichardt 1978). It demonstrates how the observers familiarity with the object gradually positively increases as the static and dynamic appearance increase up to point, which might today be occupied by the Sony Robotic Dog (Figure 1.18 (2)). An object possessing limited animal-like movement, however also possessing a similar level of static appearance to inform the observer of its artificiality. However the graph shows a large 'valley' which includes objects that although statically appearing human-like do not possess similar human-like movement. Indeed Professor Mori places electrically powered prostheses with the static appearance of the human arm at the bottom of the graph promoting feelings of unease in the observer as the static and dynamic qualities of the device are not those expected by the observer (Reichardt 1978).

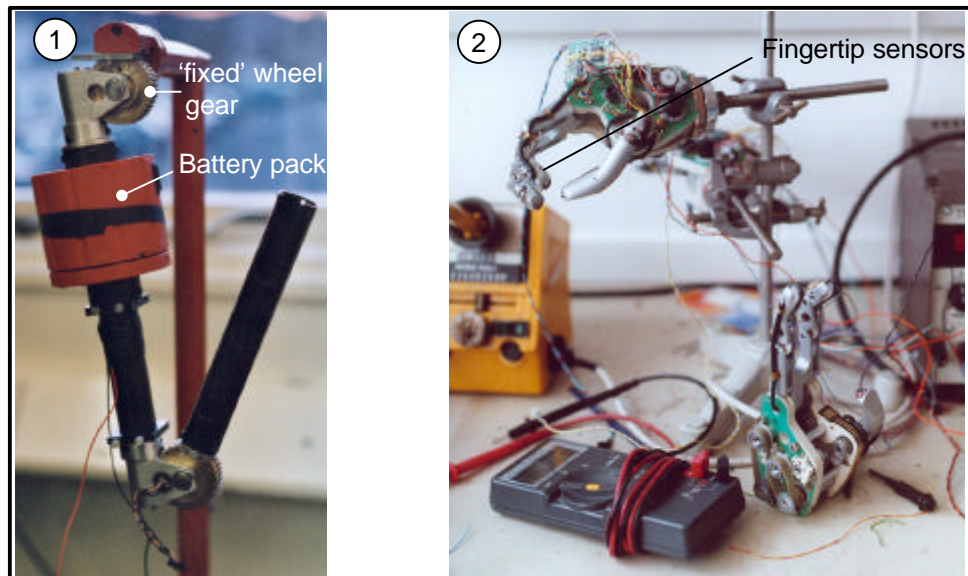


**Fig 1.19 Two Otto Bock Myoelectric Terminal Devices**

An essential feature of any active prosthesis is the functionality of the terminal device, which must replace the function of the lost hand (Scott and Parker 1988). Figure 1.19 shows two terminal devices available from the prosthetics manufacturer Otto Bock that will fit into the same socket. This starkly demonstrates the current separation of 'cosmetic' and functional devices. As described earlier, using conventional myoelectric control methods it has been found that usually only a single degree of freedom of the prosthetic device can be reliably controlled (Aghili and Haghpanahi 1995). Using the hand-like terminal device shown, the single degree of freedom relates to opening and closing of the hand in pinch grip form. The only powered movement is the motion between the thumb and first finger, the other fingers are there merely for cosmetic effect. Myoelectric control doesn't allow any direct afferent sensations from the terminal device to return to the amputee (Tura 1998). Therefore, in practice these fingers obscure the amputee's view of what is being gripped. Visual surveillance becomes vital to the amputee when other forms of feed-back have been severed (Phillips 1988); as it is often the only means available to determine the position and force applied by the terminal device (Tura 1998). Consequently, the Greiffer, above, has been specially designed to operate from a single degree of freedom control. The jaws open in a parallel motion similar to conventional robotic grippers (Crossley and Umholtz 1977). This permits a much larger grip than available from the pinch grip form of the hand-like device. Additionally, the Greiffer includes a 'wrist' that allows the device to be rotated along the axis of the forearm (pronation - supination movements), which permits greater visual surveillance of what is being gripped. The device also features distinct joints contrasting with the less durable silicone cover on the hand form which are prone to splitting (Herder et al 1998).

Alongside the multifunctional terminal devices there are many special devices that serve only to aid the amputee in particular activities (shown in figures 1.4 (3, 4)). The use of specialist devices has been advocated in UK, however, has found less favour in the USA (Banerjee 1982). This approach has obvious limitations, as the amputee must be prepared in advance with the devices needed perform the desired activities (Kyberd 1990).



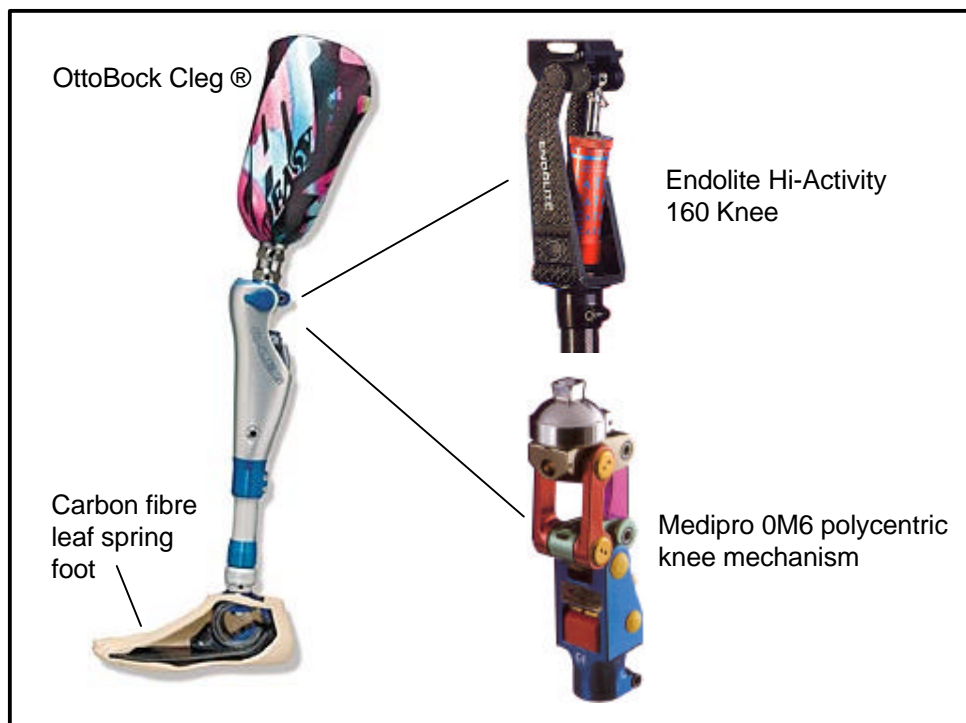


**Fig 1.20 Current Laboratories Developments of Gow and Kyberd**

Currently active research in upper-limb prostheses in the UK includes the work pursued by D. Gow in Edinburgh and Dr. Kyberd in Oxford. Gow's work builds both on the EPP work of Simpson but additionally looks to novel powered modules. The powered modules currently under development started from the need for powered digits for amputees with partial hands. Conventional myoelectric terminal device mechanisms (see figure 1.11) are inappropriate as the remaining hand occupies the space needed for the drive mechanism. Therefore, it was reasoned that the motivating device for the digit needed to be situated in the space of the prosthetic finger. It was found that, appropriately powerful motors could be integrated into the space of a normal finger. This design approach became known as 'ProDigits'. The powered modules comprise an electric motor connected through a gearbox to a 'worm' gear at the joint. When activated, the rotating worm gear propels the motor and gearbox around the fixed wheel gear. The approach proved powerful due its modularity, and so has been extended to larger modules for shoulder rotation and for elbow flexion shown in figure 1.20 (1). Currently trials are ongoing on a device that comprises powered digits, wrist elbow and shoulder movements (Gow 2000).

Research into novel control methods is being pursued by the Oxford Orthopaedic Engineering Centre under the direction of Dr. Kyberd. This research looks to embody 'intelligence' into the prosthesis to remedy some of the problems associated with using conventional electromyographic control. As the normal afferent feedback (except for vision) cannot be utilised using electromyographic control, Dr. Kyberd has integrated slip sensors into a specially designed terminal device. The terminal device design Figure 1.20 (2) comprises two 'fingers' each with three simple hinge-like joints, the last two joints being coupled together. The device possesses a powered 'thumb' that has a powered joint at its base permitting two degrees of freedom. Combined, the mechanical design, sensors and control technology result in device that on contact with an object 'chooses' which grip is optimal and only grips with sufficient force to stop the object being gripped falling from its grasp. Currently, Dr. Kyberd is looking to exploit the opportunities embedded microcontroller chips may have for tailoring control strategies to the individual (Kyberd 2000).

## Comparisons with Prosthetic Lower-Limbs



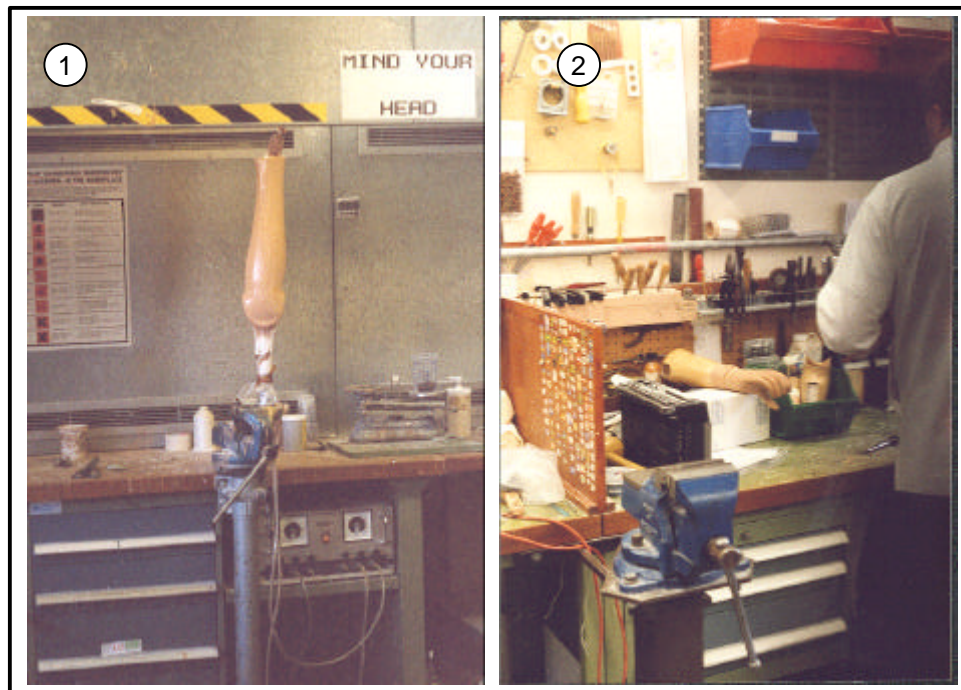
**Fig 1.21 Lower-limb Prosthetic Components**

It is often remarked by amputees' that prosthetic lower limbs appear more advanced than upper-limbs. Therefore, it is appropriate to be aware of contemporary prosthetic lower-limbs. The figures above show components available for the amputee with an above knee amputation. It can be seen from the figure that the constructional materials are much more evident; such as the carbon fibre braid in the Endolite products, and the highlighting of metallic components through high polish or anodisation.

However, the common functions of lower limb must be appreciated if a objective comparison is to be made between upper-limb and lower-limb prostheses.

Observing the figure; like the upper-limb the lower-limb featured has only a single degree of freedom, the movement at the knee. However, in conjunction with a sprung foot component, (C-Leg above) this single degree of freedom has been found to provide a convincing walking gait (Engerstrom and Van der Ven 1999). Western dress codes mean that the lower-limb can remain covered, whilst the upper-limb is usually uncovered (Robertson 1978). Consequently, the convincing gait can often disguise the absence of leg segments from observer although cosmetic covers are available should more of the leg be exposed, therefore providing a satisfactory cosmesis (Engstrom and Van der Ven 1999). Mobility is the primary function of the lower limbs, therefore, current prostheses can be said to be functionally satisfactory.

By contrast the upper-limb amputee has not lost the functions of mobility but the functions of manipulation (Pons et al 1999) and a major means of sensing the world around them (Kyberd 1990). Additionally, upper-limbs are required to be far more adaptable; whilst lower limbs have to negotiate climbing man-made stairs, the upper-limb needs to be able to manipulate a vast array of man-made objects predominately designed around the anthropometrics of the intact human hand (Croney 1980).

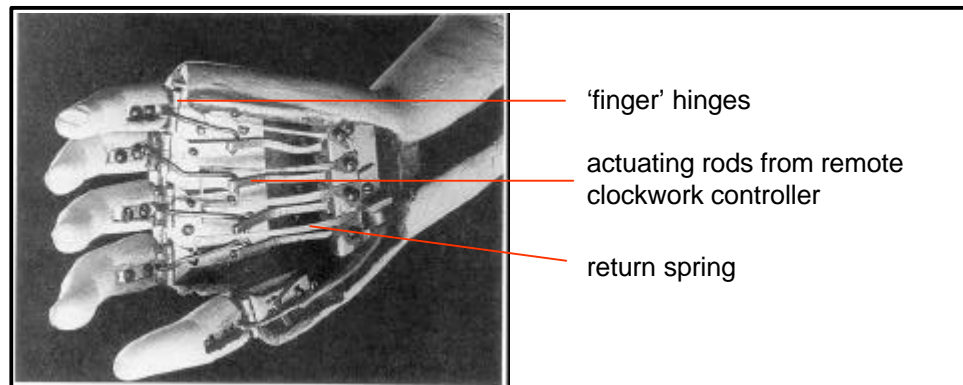


**Fig 1.22 Nottingham Limb Centre Workshops**

Figures 1.22 (1) and (2) show views of a typical workshop used by prosthetist's in the UK. Figure 1.22 (1) shows a socket being laminated from nylon stockingette and polyester resin using a vacuum method. Figure 1.22 (2) shows an array of hand tools used to finally shape the glass-fibre socket. Due to the complex individual form of the socket, craft techniques performed by skilled personnel have been chosen over machining techniques in the production of the sockets (Martin 2000); although automated production processes have been researched (Boone et al 1994). However, the individual manufacture of prostheses has been given as a reason for their expense (Aghili and Meghdari 1995).

Since the adoption of myoelectric prostheses, workshops have needed to support not only the mechanical structure but also the electrical and electronic components of the prosthesis. This has largely been achieved using large scale modularity of parts, where components such as the battery tray and electromyographic electrodes and bayonet socket for terminal device are standard and are incorporated later into the tailor-made prosthesis (Martin 2000) (figure 1.22(1,2)). Large scale modularity means that items such as the terminal device as a whole is considered a single module, as are the wrist and elbow. Consequently if standardised components malfunction they are either replaced or returned to the manufacturer for repair (Martin 2000).

In the UK amputees can be prescribed a prosthesis by the health service. This means that anyone entitled to UK health service care can be fitted with a prosthesis. However, it results in the anomaly that although the device will have been tailor made for the individual, they do not own the device. This can be problematic when the amputee experiences discomfort due to an ill fitting prosthesis. This occurs frequently, as socket discomfort has been cited as a chief problem for the amputee (Burger and Marincek 1994). Currently, minor changes to improve the comfort of an ill fitting prosthesis need to be performed by the health service. Which is not always acceptable to the amputee.



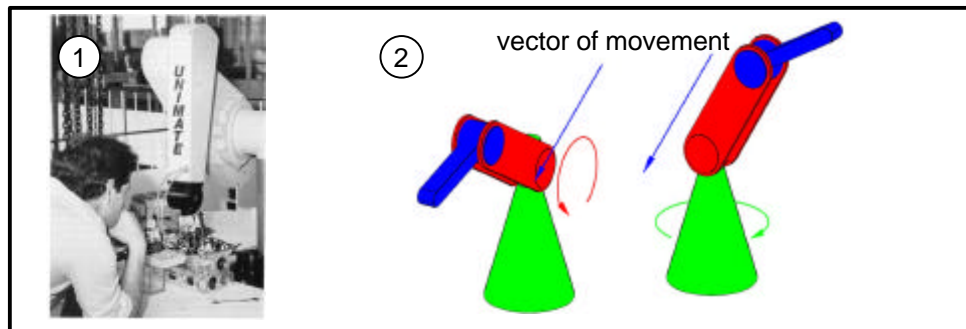
**Fig 1.23 Hand of the Musician Clockwork by Jaquet-Droz (1721-90)**

In addition to knowing the history and factors that have formed contemporary prostheses it is important to be aware of developments towards creating human-like robots known as 'Anthrobots' (Rosheim 1994). Such human-like robots have been developed for the needs to remotely manipulate either hazardous substances or to work in hazardous environments; a process known as telepresence or telemanipulation (Caldwell 1996). Human-like robotic devices are also used in the entertainment industry, referred to as animatrons (Iovine 1997). Whereas the prosthetics market is small and so research money limited, many of these robotic projects are high profile aerospace projects that command comparatively large research budgets (Rosheim 1994). However, such projects wrestle with similar problems to those faced in prosthetics, and are producing components (Herzinger 1996) and methodologies (Rosheim 1997) that may be appropriate to the field of prosthetics.

People have been interested in creating technological reproductions of the human back to the times of the ancient Greeks who used 'automata' operated by water power to re-enact significant liturgical scenes (Rosheim 1994). With the revival of interest in Greek art and culture in the Renaissance period came a refreshed interest in the production of automata. During this period Leonardo Da Vinci used his extensive knowledge of human anatomy (see methods, chapter 2) along with descriptions of the Greek automata to devise water powered clocks complete with figures that struck the hours, and designed an articulated armoured knight that could sit up, wave its arms, move its neck and open and close its jaw (Rosheim 1997). The next major development towards anthropomorphic mechanism came from the Swiss watch making industry. Inventor of the wrist watch, Jaquet-Droz (1721-90), produced three 'programmable' automata; The Scribe, The Draftsman and The Musician. Figure 1.23 shows the ingenious application of clock work technology to operate The Musician's digits (Reichardt 1978).

Whilst the above examples existed for entertainment, the advent of the industrial revolution and the consequent development of modern machine tools in the 19th century meant many tasks could be more cost effectively performed by robots than human labour. The term robot is in fact derived from the Czech 'robotnik' meaning compulsory labour (Scott 1984). The automotive industry is the chief user of robots, using robot arms to take hot, heavy castings from ovens, to spray body shells and to spot weld body panels together amongst many other tasks (Rosheim 1994). The early robots used prismatic joints, that is joints that permit translating movements similar to those found on conventional machine tools. These joints permit the accurate movement of comparatively large loads (Scott 1984).





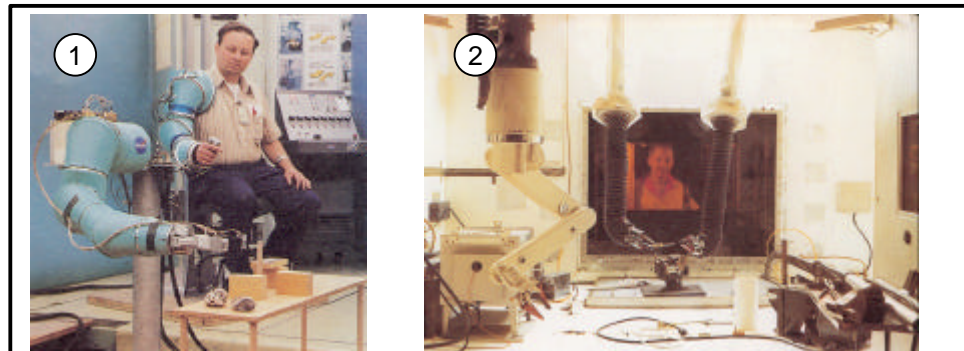
**Fig 1.24 The Stanford Robot Arm (1) and Robotic Movements (2)**

In the mid seventies research was undertaken at Stanford University to develop a new robot arm as it was found that the majority of tasks on the automotive factory floor only required the robot arm to lift a comparatively light weight of 2.3 kg but required greater 'dexterity' of the arm (Rosheim 1994). The Stanford Arm developed consists of a series of 'revolute' joints. Revolute is the term used to describe a cylindrical rotation (Schilling 1990). The arrangement of joints in the Stanford Arm allows a large 'working envelope' (reach) for a relatively small 'footprint'. This revolute joint configuration has led such robot being labelled '*anthropomorphic robots*' (Scott 1984). Figure 1.24 (1) shows a commercial example of the Stanford Arm.

The 'arm' consists of three major joints, which might be thought of as two at the '*shoulder*' and one at the '*elbow*'. These joints enable the arm to position the terminal device anywhere in the arm's working envelope (Shilling 1990). The robot arm might then possess a further three minor joints at the 'wrist' permitting 'pitch' 'yaw' and 'roll' allowing the terminal device to be placed at any angle (Scott 1984). Combined, the three major and three minor articulations then allow the terminal device to be placed at any position and angle within the working envelope of the robot arm (Schilling 1990). However, the 'anthropomorphic' Stanford arm doesn't move in the same manner as a human arm. Figure 1.24 (2) shows some of the limitations of this joint configuration. Whereas the human shoulder (gleno-humeral) joint has three degrees of freedom (Kapandji 1982), the base joint of the Stanford arm only consists of two, therefore, to achieve movement in the direction of the vector indicated requires that the base joint to be rotated to align it with direction of movement (Rosheim 1994).

Although the combination of three major and three minor simple revolute joints permits the positioning and orientation of the terminal device, this may mean that the joints have to be in a placed in a unique 'singular' arrangement to achieve a given position and orientation of the terminal device. In contrast, the human arm has more degrees of freedom, therefore, is able to position the hand in the same position with a variety of postures of the arm. This proves important, as the human being, unlike conventional robots, does not operate in a structured environment, and commonly needs to manipulate objects that are obscured by other objects. This requires extra degrees of freedom, or redundant articulations, to reach around objects (Schilling 1990).

Simple revolute joints have been chosen as they are relatively simple to accurately and powerfully actuate, meeting the historical needs of the robotic market, load capacity and accuracy (Rosheim 1994). Commonly, robots work in structured environments (Schilling 1990), and providing these extra 'redundant' degrees of freedom to robotic joints increases mechanical complexity (Rosheim 1994) and programming sophistication (Okada 1982).



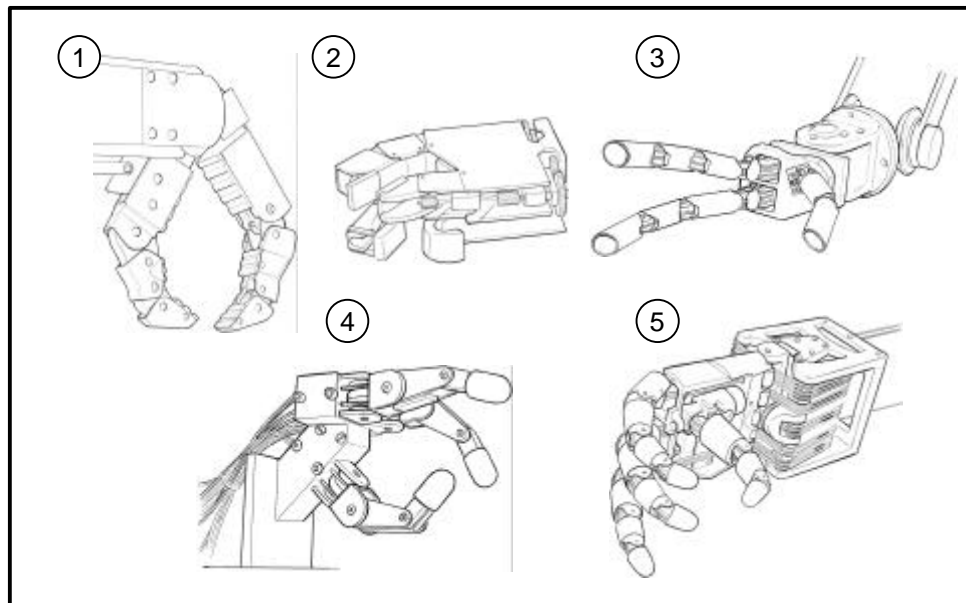
**Fig 1.25 Telemanipulators for space (1) and (2) nuclear applications**

One of the major factors that has driven the development of human-like robotic hands has been the needs of the nuclear and space industries for remote manipulation, or telemanipulation figures 1.25(1,2) (Caldwell 1995). Typical robotic terminal devices designed for manipulation consist of jaws that grip in a parallel motion (Schilling 1990). Although these devices have been shown to be very versatile, they encounter problems using tools designed around the anthropometrics of the human hand such as using a screw driver; which require a conformable grip (Crossley and Umholtz 1977).

Figure 1.26 (1), over page, shows a robot hand designed in the 1960's by General Electric to fit onto the end of a slave robotic arm for nuclear applications. This contrasts with conventional robotic parallel grippers as the series of revolute joints permits a conforming grip (Rosheim 1994).

The control of the robotic hand increases in sophistication as the degrees of freedom (D.O.F) allowed by the joints increase (Okada 1982). Therefore, early robotics research aimed to limit both the degrees of freedom of the joints and the number of digits of the hand (Crossley and Umholtz 1977). In the 70's a three-fingered hand robotic was designed (figure 1.26 (2)), on the basis that the hand would only be required to perform limited tasks. These researchers' concluded that three-fingers with simple single DOF revolute joints, were the least possible to perform such tasks as operating an electric drill with a trigger switch (Crossley and Umholtz 1977). Parallel research in Japan aimed to further increase robotic hand dexterity by including joints at the base of the fingers that permitted both simple revolution combined with side to side rotation (Okada 1979) (figure 1.26 (3)). It was found that these extra articulations permitted the robotic hand to achieve many more functions including fastening a nut to a bolt (Okada 1982).

Independent research at the Jet Propulsion Laboratory resulted in a similarly configured three-fingered hand (Mason and Salisbury 1985) (figure 1.26 (4)). The kinematic design of this robot hand came from optimising methods, where many joint configurations were considered and judged against how effectively they could both impart arbitrary forces and velocities to a grasped object and also how effectively the different grasps constrained an object (Mason and Salisbury 1985). The robotic hands of Okada and Salisbury are actuated by steel cables. In general using this method requires two opposing cables to control a single degree of freedom. Okada linked these cables together around a pulley. However, in the Salisbury hand separate motors are used on each cable to limit friction effects caused by pretensioning the system (Salisbury-Mason 1985). Both these three fingered hands have ranges of movement larger than those of the human hand (Salisbury and Mason 1985, Okada 1979). Salisbury's optimisation approach contrasts with design of the Utah/MIT hand which appears much more anthropomorphic, figure 1.26 (5).

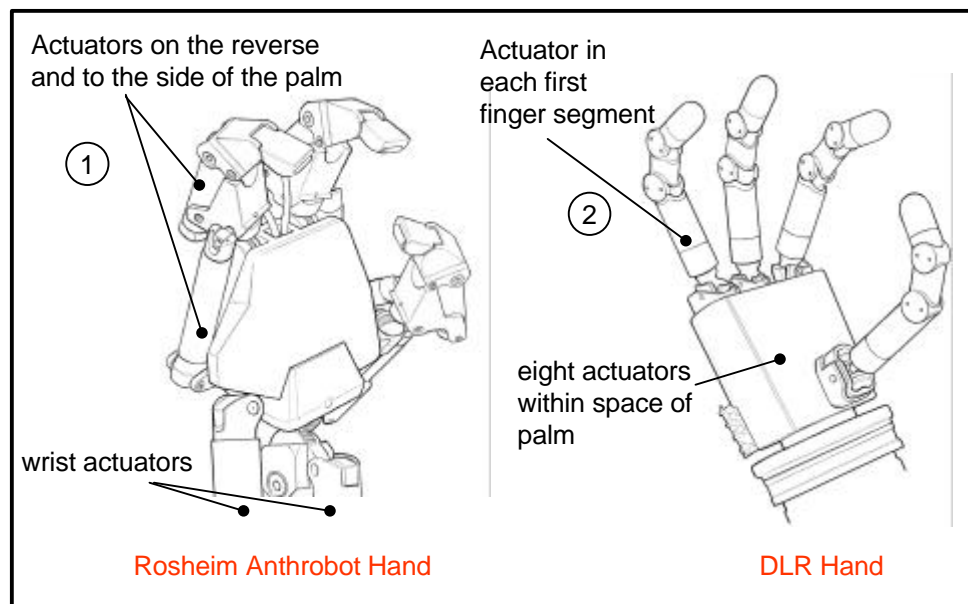


**Fig 1.26 Robotic Hands of the 1970's and 1980's**

The reasoning used for configuration of joints of the Utah/MIT hand was that the dexterity of the human hand proves the anthropomorphic arrangement of joints successful (Jacobsen et al 1984). The Utah/MIT hand has four fingers to provide a 'redundant' finger to add security to the grasp of an object. Like the previous three-fingered hands it is cable operated to limit its weight and bulk and so reduce inertial effects when connected to a robot arm (Jacobsen et al 1984). It comprises similar modular digits, with three simple revolute joints and a side to side joint at the base. The base joint is non-anthropomorphic due to the difficulties of routing tendons around this joint (Jacobsen et al 1984). Unlike the previous three-fingered hands the tendons are not powered by DC electric motors (Okaka 1979, Mason and Salisbury 1984). Instead, specially developed glass pneumatic cylinders are used operated from novel two stage valves (Jacobsen et al 1984).

It has been found that the minimum number of fingers required for grasping is three, whilst for manipulation and regrasping four are needed (Pons et al 1999). Consequently, the Utah/MIT hand is the only hand shown above with the potential of manipulating an object within its grasp. Unlike the previous hands it also comprises an 'anthropomorphic' three degree of freedom wrist to orientate the palm (Caldwell et al 1995).

Versions of the Utah/MIT hand have been made available to researchers in control, prompting criticisms of the hand where it departs from the configuration of the human hand (Perlin et al 1989). These deviations have become particularly noticeable when a human hand within a 'dataglove' is used for control. Additionally, problems have become apparent when the hand is required to use tools designed around the anthropometrics of the human hand (Perlin et al 1989). The early version of the Utah/MIT hand pictured has a oppositional 'thumb' in the middle of the palm, to enable the same components to be used as either left or right hands (Jacobsen et al 1982). However, this placement is problematic when the hand needs to grip a screw driver which requires the thumb to follow the long axis of the screw driver (Perlin et al 1989).



**Fig 1.27 Robotic Hands of the 1990's**

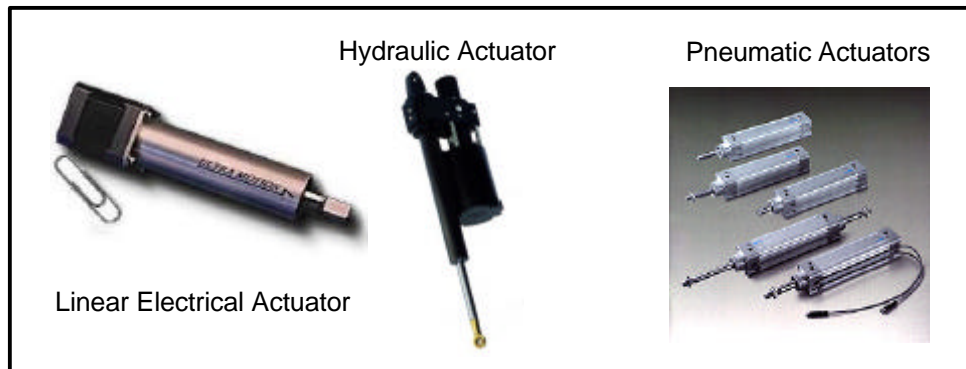
As a solution to this problem, control researchers using the human hand to control or instruct the Utah/MIT hand have developed software 'tools' that are able to 'map' the most appropriate grip configuration onto the robot hand from the controlling human hand (Bing Kang and Ikeuchi 1997).

The mechanical, and control complexity of the tendon driven hands have led to the design of hands which include local actuation (Lin and Huang 1996, Peiffer 1996). Due to limitations of conventional actuators, designers in the development of the two hands above have had to develop their own electrical actuators (Rosheim 1994, Herzinger 1995). Consequently, the resulting designs are largely based around their methods of actuation (Rosheim 1994, Liu et al 1999).

Figure 1.27 shows a robotic hand designed by Rosheim (Rosheim 1994). This uses a specially designed actuators, indicated on the figure, that can be used in thrust and tension, unlike human skeletal muscle which can only actuate joints in tension (Smith et al 1996). Two actuators are used to move the 'wrist' and these are situated in a forearm position. Actuators that move the fingers are placed on the reverse of the hand, whilst actuators for the side to side motions of the base joints of the fingers placed on either side of the palm (Rosheim 1994).

The DLR (translated acronym: German Aerospace Research Establishment) actuator uses a high efficiency motor linked through a novel 'planetary roller' gearbox to convert the revolutions of the motor to a linear motion. These units are placed both in finger segments and in the palm to move the fingers (Herzinger 1996). This has resulted in a roughly anthropomorphic geometry, however, it is 50 percentage larger than a human hand (Liu et al 1999).

Both the hands above use sophisticated actuators based on electromagnetic principles. However, currently there is research into actuators that convert electric energy more directly into mechanical energy, and may be closer to human muscle. Therefore, these actuators may be more appropriate for application to a future prosthesis (Pons et al 1999).



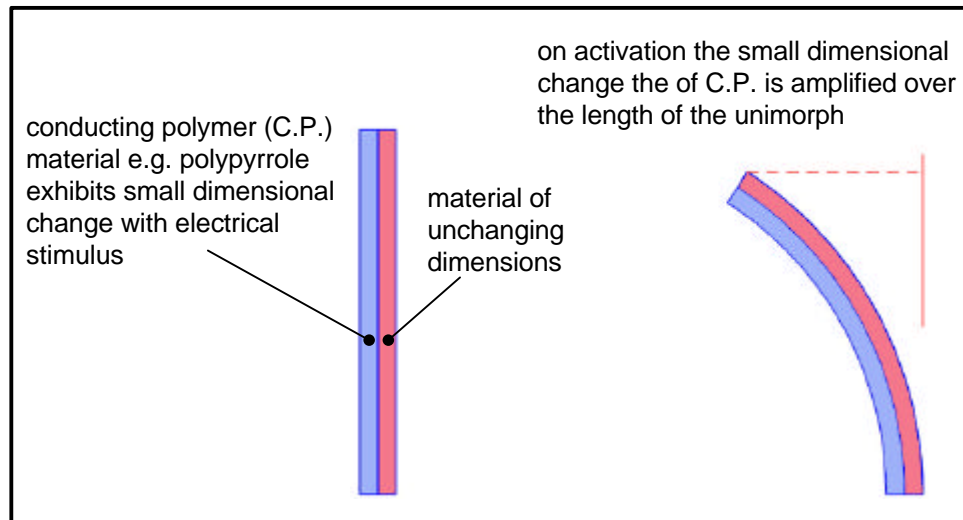
**Fig 1.29 Commercially Available Actuators**

Conventional actuators such as electrical motors, hydraulic and pneumatic cylinders are not ideal for prosthetic or robotic application (Pons 1999). Electric motors require gearing to convert the high speed revolutions of the motor armature into powerful linear or revolute motions suitable for prostheses. Unavoidably this gearing results in undesired added weight and bulk. Hydraulic cylinders require bulky control valves for electrical control, and pneumatics additionally present unwanted exhaust noise (Kyberd 1990). Consequently, developments towards 'artificial muscle' or electrochemomechanical (ECM) actuation technologies may be appropriate for future prosthetic devices (Baughman 1996, DeRossi et al 1992, Lawrence et al 1993).

In the 50's a large volumetric change was observed in water swollen polymer gels in response to immersion in solutions of either acid (for contraction) or alkali (for dilation). Consequently these materials have become known as 'pH muscles' (Caldwell 1993). Typically experimental polymer gel actuators have been configured from either thin strips (Caldwell 1990) or bundles of thin fibres (30 microns - approximately the thickness of a human hair) (Brock et al 1994). Since chemical stimulation relies on diffusion into the fibres, thin fibres contract much more rapidly as the rate of contraction is inversely proportional to the square of the thickness of the contractile element (DeRossi et al 1992). However, chemical stimulation is not ideal. It requires hydraulic valves, electrical pumps and a supply of acid and alkali as the solutions cannot be fully recycled. Therefore when the chemicals combine a salt and water waste product is formed (Caldwell 1993).

Consequently, it is seen as preferable to directly convert electrical energy to mechanical work (DeRossi 1992). Early attempts were made at electrical stimulation by placing PAN (polyacrylonitrile) fibres in a strong electric field created between two metallic plates within an electrolyte solution (Salehpoor et al 1996). Unfortunately, the water within the polymer gels would easily electrolyse and generate gases that would spoil the actuator (Toshihiro et al 1994). Consequently, similar experiments have been devised using polymer gels swollen with other chemicals (dimethyl sulfoxide) that are not so easily electrolysed and therefore allow repeated activation in a strong electric field (2.5 kV DC) (Toshihiro et al 1994).

However, despite these modifications polymer gel type materials can only generate the forces and rates of contraction approaching those of skeletal muscle when stimulated chemically (DeRossi 1992). The polyelectrolyte gels have become known as the first generation of artificial muscle (Otero and Sansinera 1996).



**Fig 1.30 Unimorph Conducting Polymer Actuators**

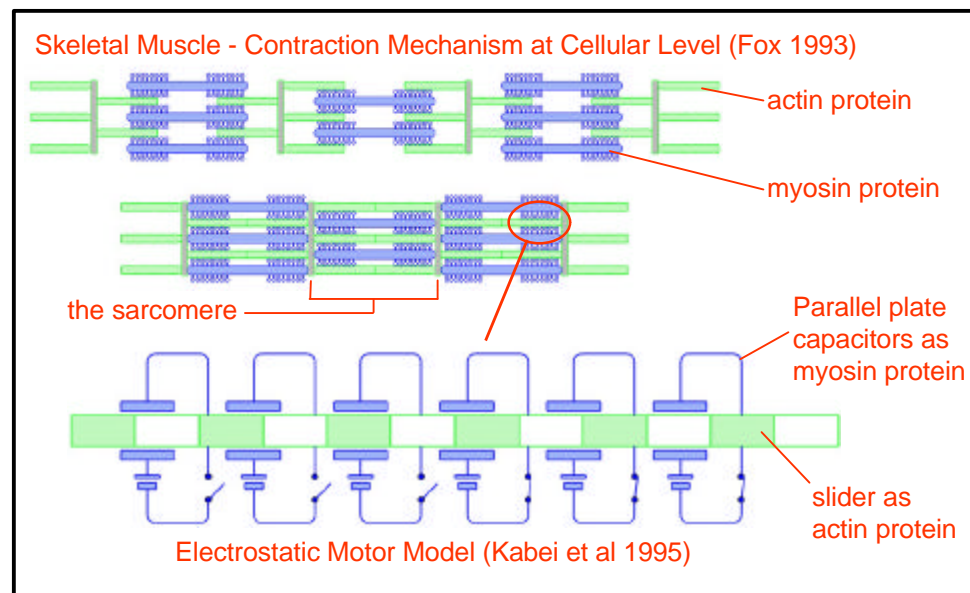
To be electrically stimulated the first generation materials required to be between two separate electrodes in an electrolyte bath, however, the second generation materials can be used as electrodes themselves (Baughman et al 1990 and Otero and Sansinena 1997) since they are electrically conducting. When used as electrodes conducting polymers have been shown to react much more rapidly than polyelectrolyte gels - in the order of seconds rather than 10's of seconds (Della Santa et al 1997). However, the percentage dimensional changes (strains) are smaller than those of first generation materials (between 0.5 and 10 percent) (Della Santa et al 1997, Baughman et al 1990), but, the force per unit area (stress) produced is comparatively large (Smela et al 1995).

Consequently, mechanical configurations have been devised that can amplify these small strains and make use of the potentially high work capacity of these materials (Della Santa et al 1997).

Figure 1.30 shows the most common experimental configuration, termed the unimorph. The unimorph configuration uses a thin strip of material of unchanging dimensions connected to the conducting polymer strip. On activation the combination bends until an equilibrium of forces is reached. Conducting polymers appear particularly appropriate to prosthetics as their action is silent, and once in the given position no further energy is needed to maintain position (Kaneto et al 1995).

Shape memory alloy has also been put forward as a possible prosthetic actuator (Pons et al 1999, Kuribayashi et al 1994). Materials such as Nitinol (a nickel titanium alloy) change dimension with temperature. Drawn into thin wires these intrinsically conducting materials can be activated by the heating effect ( $I^2 R$ ) of electrical current passing through the thin wire. The wire typically contracts by 5 percent with a temperature rise from 30 to 70 degrees (Delaey 1974). The drawback of these devices is that for a complete cycle the wire needs to cool, commonly a process much longer than that of heating. Additionally, the heat is usually dissipated to atmosphere so that although light and powerful the actuators are comparatively inefficient.





**Fig 1.31 Electrostatic Linear Actuator** (Kabei et al 1995)

Most of the actuators previously discussed operate much slower than human muscle, which typically can contract at rates of 500% per second (Caldwell 1993).

Searching for a fast response rate has made electrorheological fluids (ER fluids) attractive. Application of a strong electric field across an ER fluid increases the shear forces within the fluid (Stangroom 1999). Devices have been constructed that use ER fluid as a type of valve (Tanaka and Tsuboe 1994). The speed of such response is such that when connected to a speaker cone they can produce audible music (Stangroom 1999). Other researchers have combined the ER effect with electrodes fixed within a flexible material. Electrodes with a strong electrical field between them will be attracted to one another (Bohon and Krause 1998). An experimental test rig has been devised in which two electrodes are fixed within an elastic medium that is mixed with ER fluid. When a strong field is applied between the electrodes the electrodes move together until the ER fluid within the elastic material stiffens to stop them. On releasing the field the elastic nature of the material restores the electrodes to their initial position. This experiment has demonstrated electrode movements up to a frequency of 15 cycles per second (15 Hz) (Bohon and Krause 1998).

Although ER fluids are fast acting, high voltages are required for their operation (typically kV) which makes them inappropriate for prosthetic applications.

Other actuators that have been devised utilising dimensional change caused by piezoelectric or electrostrictive phenomena (Shinsei Kogyo 1985, Uchino 1986). However, commonly these produce this is less than 0.1% strain on activation and require relatively high operating voltages (100's volts) (Baughman et al 1990).

Other actuators have been developed that although not electrochemomechanical in their action have been likened to human muscle in their structure. Such actuators have been referred to as 'biomimicking' human muscle (Kabei et al 1995). Figure 1.31 shows an actuator developed by (Kabei et al 1995) working on a capacitive principle that is likened in its action to the 'sarcomere' of human skeletal muscle.

## Simultaneous control of Multiple Degrees of Freedom



**Fig 1.32 A Dataglove and The 'Magpie'**

Whatever the actuation method used, multidegree of freedom robotic hands need an effective control method. Robotic hands can be programmed at many levels including through a commercial text based language. However, the most effective method is seen as by 'data glove' control (Speeter 1992). Data gloves fit over the operators hand and record the angles of the joints of the fingers. Outputs from the transducers within the glove are linked to a computer so that joint angles can be recorded against time. From this data joint velocities and accelerations can be determined (Speeter 1992). Many data gloves have been designed and are now commercially available. These can be separated into those that purely provide data to the computer from the glove about joint position such as the VPL Research Data Glove and the Vitrex CyberGlove. However, 'powered' gloves such as Sarcos Exoskeletal Master not only record position but allow the fingers of the glove to be moved allowing closed loop control of a virtual hand (Pimentel and Teixeira 1993). Just as extended proprioception has been found to be important in the functionality of prosthetic devices (Harbres 1974(2)), such powered feedback has become an important goal in remote manipulation to enhance the operators efficiency (Caldwell 1996). This has become an important concept, known as 'telepresence' (Caldwell 1996) and research into channelling further sensations to the operator are being investigated. These include peltier effect devices included in the finger tips of the glove to simulate temperature change experienced at the slave robotic manipulator, and vibratory transducers to simulate touch sensations (Caldwell 1996). However, problems have arisen in the data glove control of current multidegree of freedom dexterous robotic hands where these manipulators divert from the geometry of the human hand (Perlin et al 1989). Production of a slave robotic hand that is closer to the human anatomy should substantially reduce some of the control problems encountered controlling current robotic devices (Caldwell 1995).

Devices exist in the medical field that aim to control multiple degrees of freedom terminal devices using inputs from other parts of the body. Figure 1.32 shows a 'Magpie' designed for people afflicted by MS (Multiple Sclerosis). This degenerative condition means that for a short period of time whilst the motor control of the upper limbs is inoperable the lower limbs are relatively unaffected, the magpie uses motion of the lower limb to guide the motions of the spoon to enable the person to feed themselves (Kyberd 2000).



### ***Development of Research Hypothesis***

Research and clinical experience have shown that amputees have a need to both appear and function normally. However current prostheses can only satisfy either a functional or a cosmetic requirement in a single device.

Due to the comparatively small market for upper-limb prosthetics, commercial research and development has focussed on incremental change on moderately successful archetypal designs. The technology used in these archetypal designs means that the number of control inputs that the amputee has control over is very limited.

Continued development along these archetypes has lead to designs where the control limitations have dictated the form of the device. This has resulted in a separation of cosmesis (an acceptable aesthetic hand-like appearance) and functionality. However, it is clear that amputees require both cosmesis and functionality in a single device; and that movement is an essential part of cosmesis. Therefore prosthetic devices are required which offer both the form and function of the human hand.

Successful control strategies for multiple degree of freedom prostheses were reported in the early 1970's, however, this research was not pursued further due to inappropriate actuation methods.

Current actuation methods have been cited as a limiting factor on the design of more complex prostheses. As it has been found that current electrical actuators cannot achieve the performance necessary for effective closed loop control. Historical designs have endeavoured to bypass this limitation by coupling the movement of many fingers together using a single actuator. However, this has not been successful as amputees require manipulative functions in addition to the grasp function provided by such devices.

Advanced robotic hand research has not been bound by the same financial, control and weight restrictions as prosthetics. Therefore, other examples of electrically and pneumatically actuated hands have been developed. However, it has been demonstrated that problems arise both in control and functionality where these robotic hands divert from the anatomy of the human hand. In many, diversions from the original anatomy have been necessitated by the actuation strategies used.

Current research into novel actuators may, however, permit multiple actuators within structures much closer to those of the human hand. Additionally, technology developed from the needs to control of objects in virtual reality environments, or remotely in hazardous environments, may indicate new methods of multiple degree of freedom control.

There is need in both the fields of prosthetics and robotics for a hand which combines both form and function. This thesis examines the development of a skeletal analogy of the human upper limb which must form the basis of any device possessing both the form and functionality of the limb.

## Hypothesis

*Many design principles appropriate for a new generation of upper-limb prostheses combining cosmesis and functionality will develop from exploring a close analogy to the skeletal articulations of the human upper-limb. Additionally, using a research method based on the production of tangible models will serve as a means of gaining useful evaluation from a wide range of interested parties.*